

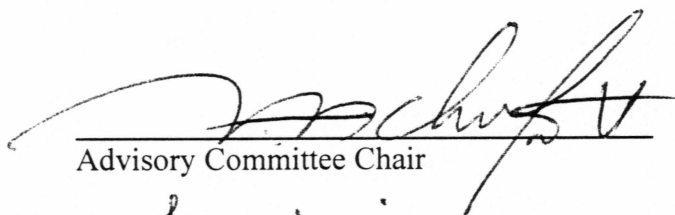


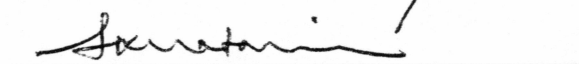
AN ECONOMIC APPRAISAL OF HOLE CLEANING USING HYDRAULIC
HORSEPOWER AND JET IMPACT FORCE

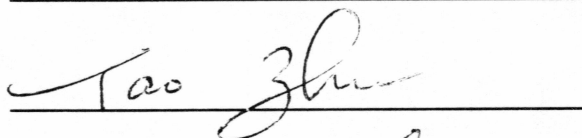
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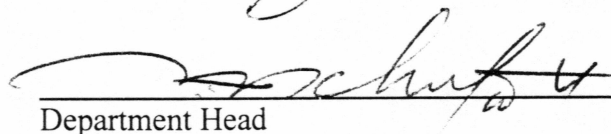
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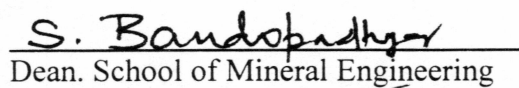

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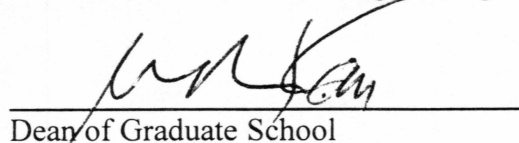


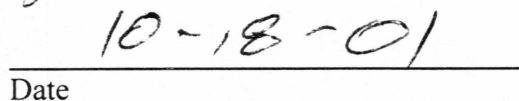



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**AN ECONOMIC APPRAISAL OF HOLE CLEANING USING
HYDRAULIC HORSEPOWER AND JET IMPACT FORCE**

**A
THESIS**

Presented to the Faculty
Of the University of Alaska Fairbanks

In Partial Fulfillment of the Requirements

For the Degree of

MASTER OF SCIENCE IN ENGINEERING

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By

James Alfred Wright

Fairbanks, Alaska

December 2001

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Abstract

In today's competitive business environment, reducing operating cost means dollars to the bottom line. One way that a drilling company can reduce operating cost is by optimizing energy use at the mud pumps. The mud pumps are massive pieces of equipment that are the backbone of the cutting's removal system. Optimizing the hydraulics program is one way to reduce mud pump operating cost.

Bit hydraulics plays an important role in the drilling process. The beneficial action of the fluid's cleaning the bottom hole and the bit teeth, and carrying particles into the annulus is well-established ¹. A variety of hydraulic optimization designs are available, however, in this study the efficiency and cost effectiveness of two methods are compared: Jet Impact force and Hydraulic Horsepower. Both methods have a fundamental objective to maximize the available hydraulics to provide optimum cleaning but Jet Impact method optimizes drilling cost better than Hydraulic Horsepower.

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Chapter 1

Introduction

1.1 Objectives

The use of kinetic energy of drilling fluid circulation when drilling a well is important in the subject of drilling hydraulics. Drilling fluid is pumped into the hole using a mud pump, to the drillstring, and discharged through the bit nozzles to the formation. Carrying cuttings from the hole bottom through the annulus, the fluid returns to the surface where the cuttings are discharged passing through the solids removal equipment which are connected in series. The proper use of hydraulic practices can eliminate the problem of inefficient bottomhole cleaning. Figure 1.1 illustrates a visualization of the concept of the hydraulic principle. The essence of a good hydraulic system is to provide adequate hydraulic power to the fluid as it comes into contact with the formation. The bit nozzles provide the force to transport the cuttings to the surface as soon as the bit teeth crater and fracture the rock. The hydraulic action of the nozzles and the design of the bit face direct the cuttings toward junk slots located on the outside diameter of the bit. Both the nozzles and junk slots provide the basic flow pattern required to clean and cool the cutters and reduce the distance cuttings must travel to reach the borehole annulus. Insufficient hydraulic power leads to regrinding of the cuttings in the bottomhole, instead of transporting them to the surface. This hole cleaning deficiency can cause accumulation of cuttings in the bottomhole and consequently impede the rate of penetration.

Different hydraulic design programs have been presented for controlling the flow of drilling fluid across the profile of the bit. The efforts of this study are to analyze the cost effectiveness of optimizing hydraulics using jet impact force and bit hydraulic horsepower. Optimum hydraulics programs can be designed on the basis of minimum drilling cost and this study looks at how these two hydraulic methods compare with respect to cost. Data required for this type of optimization are fuel and pump maintenance hourly cost.

According to Sutko², both hydraulic horsepower and jet impact force are excellent hole cleaning methods, and the rates of penetration are almost identical using either method. This study will also assume that the rate of penetration is the same for both methods. This allows for a straightforward comparison and determinations of mud pump energy cost and pump maintenance cost for both bit hydraulic conditions.

From conversations with the head engineer at Nabors Drilling, Wayne Rust³, the cost of all maintenance and energy are included in the daily rig rate. Because the cost of maintenance and energy are not directly represented in the standard drilling cost equation, the operator of the well may not consider optimizing energy cost and maintenance cost a priority. However, optimizing these cost would be of great interest to the drilling company. By reducing its own cost, the drilling company will be more competitive with its future bids, thus, indirectly reducing the operator's cost.

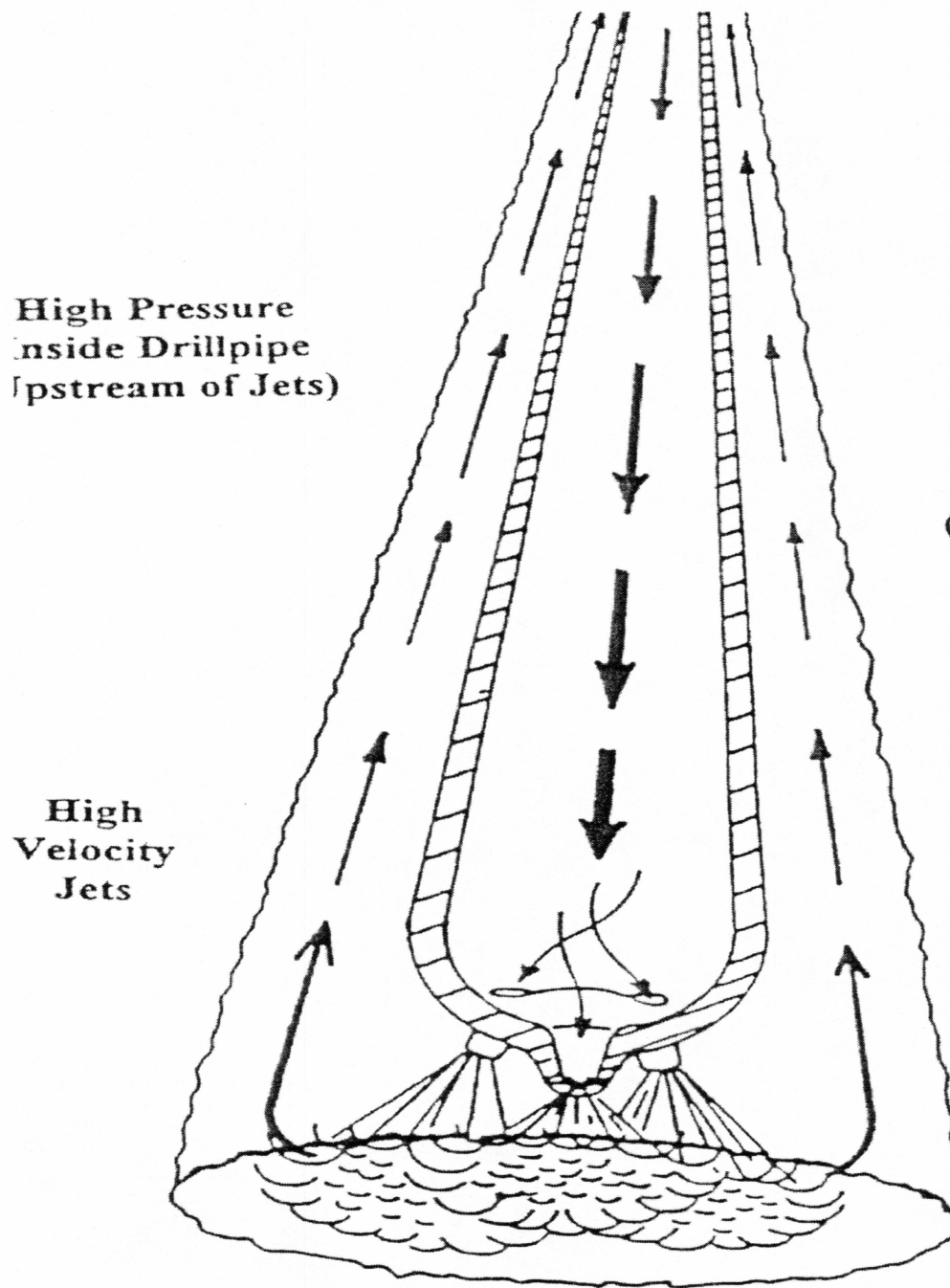


Figure 1.1: The Hydraulic Principle

Chapter 2

Literature Review

This Literature review discusses the earlier efforts by various researchers in the understanding of how nozzle sizes and nozzle adaptations affect drilling objectives and drilling cost. The review also takes a look at the parameters that affect the penetration rate and the efficacy of cutting transportation for hole cleaning.

2.1 Previous Investigation

According to Adams⁴, a complete and comprehensive mud plan must be included in the well planning process. From experimental studies done by Belavadi and Chukwu⁵, transportation of cuttings is a mechanism, which is a vital factor for a good drilling program. They concluded that not only is it important to clean the surface of the bit properly, the cuttings must be properly lifted up the annulus to avoid slippage and regrinding both which retard penetration rate. Minimum hole cleaning with out the regrinding of cuttings is essential to maximize penetration rate. Moore⁶ stated that even today many operators do not recognize the importance of bottomhole cleaning. They may use jet bits, but the circulation program is so poorly designed that bottom-hole cleaning is no better than achieved with conventional bits. He further concluded that the ultimate objective is to reduce drilling costs. The most effective means of accomplishing this is through a drilling optimization approach to drilling. Lumnus⁷ reached this same conclusion in his studies of "Drilling Fluids Optimization." Figure 2-1 is a schematic of cuttings transport in a vertical annulus.

Optimization using roller cone bit hydraulics has been debated for many years. There is still no consensus of opinion on what parameter should be optimized (bit hydraulics or jet impact) to provide maximum rate of penetration. Because Kendal and Goins⁸ felt that as little as 50 percent of the possible effects at the bit are used in most drilling projects, they presented derivations that established criteria for maximizing hydraulic horsepower, and jet impact within constraints imposed on pump horsepower and discharge pressure. Evaluation by hydraulic horsepower is based on the power expended as the fluid flows through the nozzles. The parameter optimized by the impact force method is the force produced by momentum change after the fluid exits the nozzles and reaches the bottom of the hole. Eckel⁸ recommended maximizing Reynolds number function associated with jet velocities based on laboratory results in microbit drilling studies that considered viscosity effects. Bizanti⁹ created a Reynolds Number Criterion system based on some of the same work as Eckel⁸. Others have suggested maximizing Jet Velocity to achieve optimized hydraulics. Smalling and Key¹⁰ concluded that maximum jet impact pressure in the formation explained observed effects of extended nozzles and blanked nozzles and that it is the key parameter in hydraulic optimization.

Many other researchers have suggested optimizing hydraulics by extending nozzles and using blanked nozzles. According to Sutko¹¹, present day methods can be made more efficient by lowering cost and by better utilization of the hydraulic energy. He contented that better use of energy is obtained by using two nozzles instead of three. Surface pressure and annular velocity can be reduced without a loss in penetration rate, or, by maintaining current annular velocities and surface pressure, hole cleaning can be increased. Sutko¹¹ also stated that jet impact force and hydraulic horsepower are the best

technique and they can practically achieve the same efficiency in hole cleaning. He also did some work with Myers¹², which showed improvements in bottom-hole cleaning by using extended nozzles. However, according to Adams⁴, the extra cost of the custom machine work required on the bit, and because the extended nozzles tend to break-off in field operations, extended nozzles may be unjustifiable.

Most proposed optimization criteria consider pump-operating conditions to be fixed. That is, they seek to maximize rate of penetration within prescribed constraints on flow rate, and pump horsepower. Studies performed by Doiron and Deane¹ showed that hydraulic horsepower and jet impact force have values within 92 percent of their maximum values when either parameter is maximized. This is one reason why it has been difficult to prove the superiority of either condition or the closely related conditions of maximum cross flow velocity or impact pressure in field or laboratory drilling tests. In practice, any of these optimization criteria can be expected to give good results. However, any of these criteria can result in poor bit hydraulics when effects of the pump operating constraints are ignored.

Even though many papers have been written on the merits of different hydraulic optimization techniques, very little has been published about the economic impacts of optimizing these different hydraulic systems. Mitska and Skalle¹³ considered the effects of pump constraints and suggested conditions for maximizing effective rate of penetration by including lost drilling time due to pump failures at higher discharge pressures. However, drilling cost was not considered in their analysis. Doiron and Deane¹ evaluated the work of Mitska and Skalle¹³ on drilling economics. They concluded

that modest increase in standpipe pressure could result in large percentage increases in hydraulic horsepower, which results to improvement in rate of penetration.

2.2 Selection of Study Parameters

The objective of this work is to analyze and compare the economics of using the Hydraulic Horsepower method and the Jet Impact Force for optimizing hydraulics for hole cleaning. From the determination of optimum bit nozzle sizes for efficient borehole cleaning for both Hydraulic Horsepower and Jet Impact Force, the cost for each optimum method was determined, analyzed and the results were used for comparative study of the two methods.

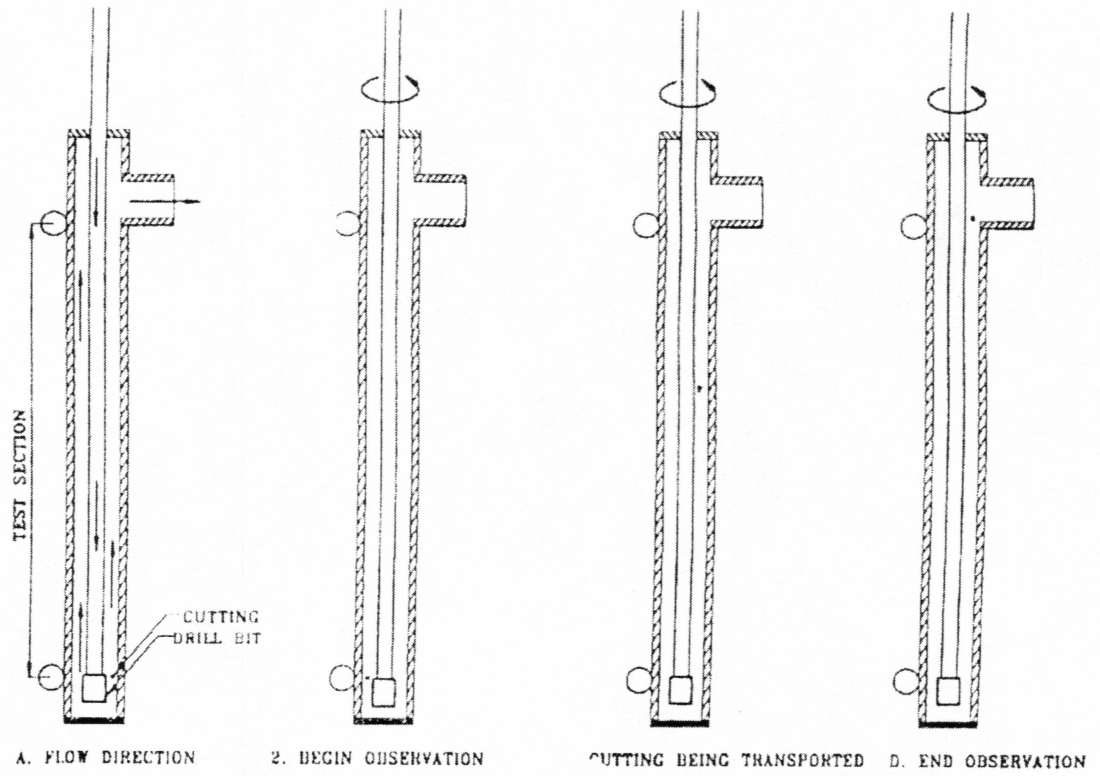


Figure 2.1: Cuttings Transport in Vertical Annulus

Chapter 3

The Theory of Drilling Hydraulics

Drilling hydraulics is a subject associated with the kinetic energy of fluid circulation when drilling a borehole. In drilling operations, drilling fluid is initially discharged from the mud pump, passes through surface connection, enters the drillstring, and discharges into the bottomhole via the bit nozzles. The fluid returns to the surface carrying cuttings from the bottomhole via the annulus. Figure 3.1 shows the schematic of the bit nozzle. Bit hydraulics is related to the effects of number and sizes of the nozzles, and the jet velocity of drilling fluid passing through the bit nozzles, and the pressure loss across these bit nozzles.

3.1 Determination of a Particle Reynolds Number:

Particle Reynolds number is a dimensionless group used to determine the fluids flow regime or profile. The equation used to determine the particle Reynolds number as a function of slip velocity of the solid, which is given by equation 3.1.

$$N_{re} = \frac{15.47 \rho V_{so} d_s}{\mu_a} \quad (3.1)$$

Where,

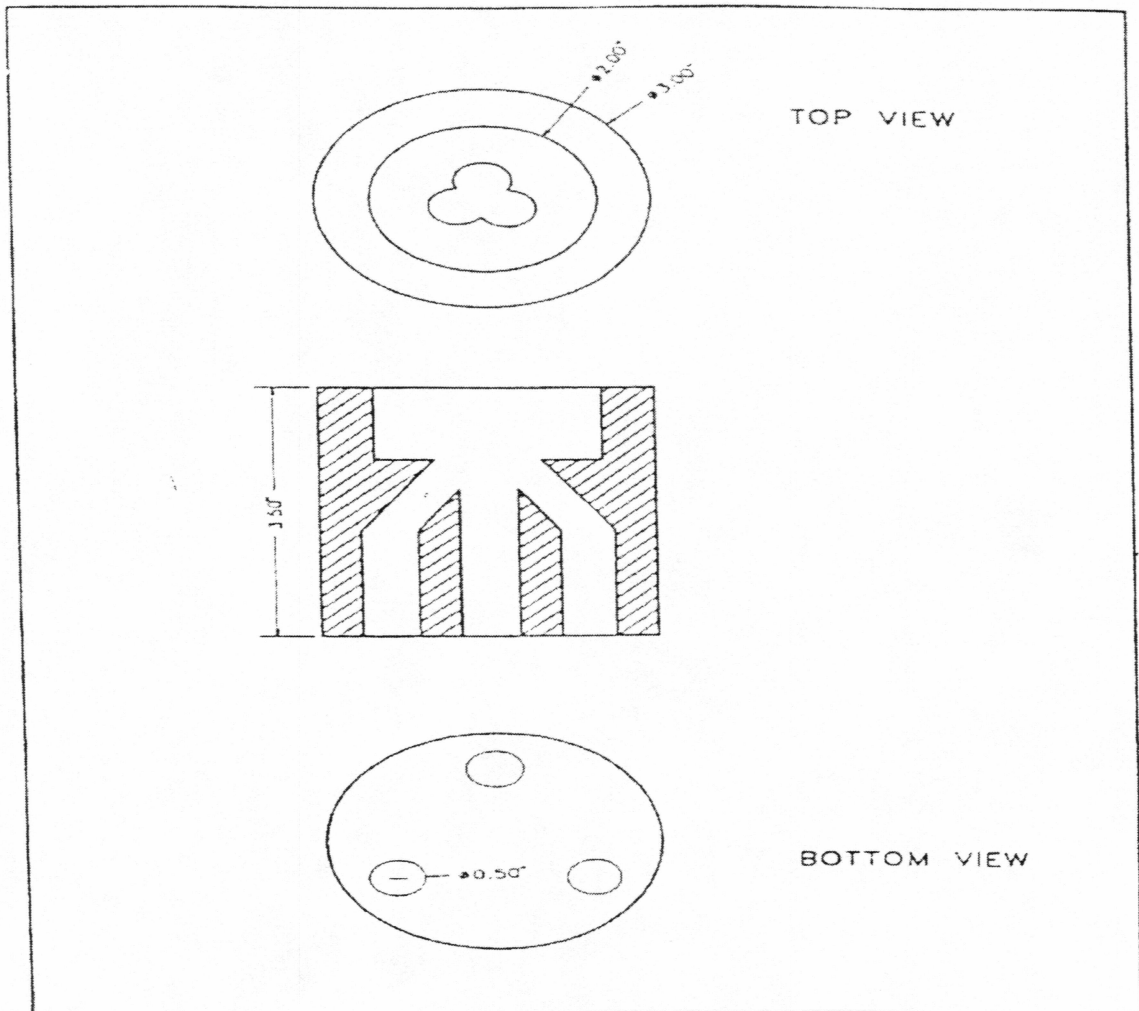


Figure 3.1: Schematic of the Bit Nozzle

$$\mu_a = \left[\left(\frac{2.4V_a}{Di - d_o} \right) \left(2n + \left(\frac{1}{3n} \right) \right) \right]^n \left[\frac{200K(Di - d_o)}{V_a} \right] \quad (3.2)$$

and,

- ρ = Density of the fluid ppg
 V_{so} = Slip Velocity of the particles ft/min
 ds = Diameter of the solids being transported, in.
 μ_a = Apparent Viscosity, cp
 D_I = Inner diameter of the hole, in.
 d_o = Nozzle equivalent diameter, in.
 K = Power Law fluid consistency index factor
 n = Power-Law fluid flow index factor
 V_a = Fluid average velocity ft/min

3.2 Effects of Drag Coefficient

Drag coefficient is a measure of the magnitude of frictional forces acting on the moving solid in a liquid medium. Empirical equations had been used to compute the drag coefficient as a function of particle Reynolds number.

$$C_d = 1.5 \quad \text{for} \quad N_{re} > 300 \quad (3.3)$$

$$C_d = 22/(N_{re})^{0.5} \quad \text{for} \quad 3 < N_{re} < 300 \quad (3.4)$$

$$C_d = 40/(N_{re})^{0.5} \quad \text{for} \quad N_{re} > 3 \quad (3.5)$$

3.3 System Pressure Losses in a Circulating System

The pressure losses in the entire circulating system can be obtained as:

$$P = \Delta P_{sys} = \Delta P_{sc} + \Delta P_{dpin} + \Delta P_{dcin} + \Delta P_{dpa} + \Delta P_{dca} + \Delta P_b \quad (3.6)$$

The system pressure loss is therefore made up of the pressure loss across the bit (ΔP_b), and the parasitic or circulating pressure loss (ΔP_c), that is,

$$P = \Delta P_{sys} = \Delta P_c + \Delta P_b \quad (3.7)$$

Where,

$$\Delta P_c = \Delta P_{dpin} + \Delta P_{dcin} + \Delta P_{dpa} + \Delta P_{dca} + \Delta P_{surface} \quad (3.8)$$

3.3.1 Pressure losses at the Bit

The pressure drop across the bit has a number of practical applications, which include:

1. Enabling the engineer to select nozzle sizes to optimize the hydraulic horsepower or impact force at the bit. This improves cuttings removal and bottomhole cleaning.
2. Providing a means of comparing observed standpipe pressure with the total circulated pressure drop. This enables the pump volumetric efficiency to be estimated. A drop in volumetric efficiency usually gives an early warning of pump failure.

3.4 Bit Hydraulics Optimization

3.4.1 Optimum Hydraulic Horsepower(HHP)

The hydraulic horsepower at the bit can be determined from the relationship given in equation 3.9.

$$HHP = \frac{\Delta P_b Q}{1714} \quad (3.9)$$

The expression of HHP in terms of pump pressure and circulating pressure loss can be obtained from equation 3.10.

$$HHP = \frac{Q(P_p - \Delta P_c)}{1714} \quad (3.10)$$

Although, the circulating pressure losses are directly proportional to the flowrate of drilling fluid, the relationship may not be linear, and therefore the relationship can be expressed as:

$$\Delta P_c = kQ^m \quad (3.11)$$

Due to difference in wellbore geometry, the relationship above can be expressed:

$$\Delta P_c = K'Q^m \quad (3.12)$$

where m is the flow exponent constant, and K' is a constant representing mud properties and wellbore geometry.

Substituting equation 3.12 for ΔP_c into equation 3.10, the relationship of equation 3.13 is obtained.

$$HHP = \frac{P_p Q - K' Q^{m+1}}{1714} \quad (3.13)$$

which can be expressed as:

$$HHP = \left(\frac{1}{1714} \right) [P_p Q - K' Q Q^m] \quad (3.14)$$

The flowrate at which the bit horsepower is maximized is obtained by differentiating equation 3.14 with respect to flowrate, as follows:

$$\frac{\partial(hhp)}{\partial Q} = \left(\frac{1}{1714} \right) [P_p - (m+1)K' Q^m] = 0 \quad (3.15)$$

Rearranging equation 3.15, the relationship of pump pressure and circulating pressure loss can be expressed as:

$$P_p = (m+1)K' Q^m = (m+1)\Delta P_c \quad (3.16)$$

or,

$$\frac{\partial(hhp)}{\partial Q} = 0 \quad \text{when } P_p = (m+1)\Delta P_c \quad (3.17)$$

Therefore at optimum pump pressure, the optimum circulating pressure losses $\Delta P_{c(opt)}$ can be expressed as:

$$\Delta P_{c(opt)} = \left(\frac{1}{m+1} \right) P_p \quad (3.18)$$

And the optimum pressure drop across the bit can be expressed as:

$$\Delta P_{b(opt)} = P_p - \Delta P_{c(opt)} = \left(\frac{m}{m+1} \right) P_p \quad (3.19)$$

The optimum flowrate can then be expressed as:

$$Q_{(opt)} = \left(\frac{\Delta p_{c(opt)}}{K'} \right)^{\frac{1}{m}} \quad (3.20)$$

The optimum nozzle sizes can be calculated from equation 3.21 as:

$$d_{(opt)} = \left[\frac{17.3 \rho Q_{(opt)}^2}{K'} \right]^{0.25} \quad (3.21)$$

3.4.2 Optimum Jet Impact Force(JIF)

The jet impact force indicates the force exerted on the formation through the jet nozzle. The impact force developed by the bit can be expressed as:

$$F_j = 0.01823 C_d Q (\rho \Delta P_b)^{0.5} \quad (3.22)$$

The JIF is related to the fluid flowrate and nozzle velocity by:

$$F_j = \frac{\rho Q V_n}{60g} = \frac{\rho Q V_n}{1932} \quad (3.23)$$

But,

$$\Delta P_b = \frac{\rho V_n^2}{1120} \quad (3.24)$$

Where the nozzle velocity can be determined from:

$$V_n = \left(\frac{1120 \Delta P_b}{\rho} \right)^{0.5} \quad (3.25)$$

Substituting equation 3.24 and 3.25 into equation 3.23,

$$F_j = \frac{\rho Q K_1 \Delta P_b^{0.5}}{60g} = K_2 \left[Q^2 (P_p - K' Q^m) \right]^{0.5} \quad (3.26)$$

where,

$$K_2 = \frac{\rho K_1}{60g} \quad \text{and} \quad K_1 = \sqrt{\frac{1120}{\rho_m}} \quad (3.27)$$

The flowrate at which JIF is maximized is obtained by differentiating equation 3.27 with respect to flowrate, as follows:

$$\frac{\partial F_j}{\partial Q} = K_2 \left[Q (P_p - K' Q^m) \right]^{0.5} = 0 \quad (3.28)$$

That is,

$$2QP_p - (m+2)K'Q^{m+1} = 0 \quad (3.29)$$

or,

$$2QP_p = (m+2)K'Q^{m+1} \quad (3.30)$$

Which can be simplified to obtain:

$$P_p = \left(\frac{m+2}{2} \right) \Delta P_{c(opt)} \quad (3.31)$$

The optimum circulating pressure loss can then be obtained as:

$$\Delta P_{c(opt)} = \left(\frac{2}{m+2} \right) P_p \quad (3.32)$$

Similarly, the optimum pressure loss across the bit can be obtained from:

$$\Delta P_{h(opt)} = P_p - \Delta P_{c(opt)} \quad (3.33)$$

$$\Delta P_{h(opt)} = P_p - \left(\frac{2}{m+2} \right) P_p \quad (3.34)$$

so,

$$\Delta P_{h(opt)} = \left(\frac{m}{m+2} \right) P_p \quad (3.35)$$

The optimum flowrate can then be expressed as:

$$Q_{(opt)} = \left(\frac{\Delta P_{c(opt)}}{K'} \right)^{\frac{1}{m}} \quad (3.36)$$

The optimum nozzle sizes can be obtained from the following equation:

$$d_{(opt)} = \left(\frac{17.3 \rho Q^2_{(opt)}}{K'} \right)^{0.25} \quad (3.37)$$

The specification of common nozzle sizes and their equivalent diameters are listed in appendix table A.1.

Chapter 4

Hydraulics Analysis in Rotary Drilling

4.1 Effects of Pressure Ratio and The Flow Exponent m

The determination of pressure losses in the circulating system has been an objective of technology for almost as many years as rotary drilling has been in existence. The first dedicated efforts to determine the pressure losses in fluid circulating systems developed when drilling hydraulics was introduced in 1948. A schematic diagram of the drilling fluid circulating system is shown in Figure 4.1. The total pressure loss in the entire circulating system is recorded on the surface pressure gauge. The summation of these pressures was presented in Equation 3.6.

$$\Delta P_s = \Delta P_{s.c.} + \Delta P_{dp} + \Delta P_{dc} + \Delta P_b + \Delta P_{dca} + \Delta P_{dpa} \quad (3.6)$$

During drilling operations, an increase in hole depth will affect the pressure losses in both the drillstring and the wellbore annulus. To maintain the designed

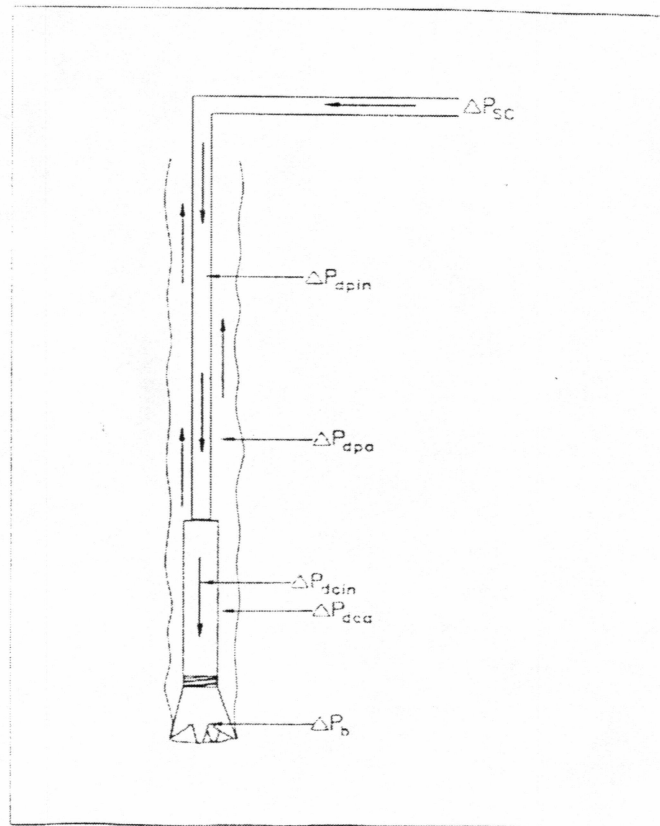


Figure 4.1: Vertical Borehole Circulating System

optimized drilling program, an increase in well depth will not change the pressure drop across the bit, however, it can greatly alter the circulation pressure loss of the system. There is a circulating pressure loss as depth increases. From the ratio of the pressure drop across the bit to the circulating pressure loss $\Delta P_b/\Delta P_c$, the optimum flowrate and optimum nozzle diameter can be calculated.

As discussed in Chapter 3, pressure loss relates to circulation rate as shown in Equation 4.2 and 4.3.

$$P_c = KQ^m \quad (4.2)$$

and,

$$P_b = K'Q^2 / A_N^2 \quad (4.3)$$

In equation 4.2, the exponent m is known as the flow exponent. A common assumption in the oil field is that the flow exponent, m , is 1.8. However, the following equation from chapter 3 shows that it can be calculated by using data from the previous bit run.

$$m = \log(P_c/P_b) / \log(Q_1/Q_2) \quad (4.4)$$

Using equations that were presented in chapter 3 tables B-1 through B-5 were tabulated for pressure ratio vs. optimum diameter. Graphical representations are also shown in figures 4.1 through 4.5. At different values of m , the ratio of pressure loss across the bit to the circulating pressure drop was calculated. The tables also present

values of $\Delta P(\text{opt})$, $\Delta P_C(\text{opt})$, $Q(\text{opt})$, $d(\text{opt})$ for both the Hydraulic Horsepower and Jet Impact Force. Data in tables B-1 through B-5 were obtained using the assumed flow exponent value(m) of 1.8. The calculated flow exponent from table 4.1 (Lim¹⁴) also give the pressure losses across the bit and the flow exponent m for different nozzle combinations.

Figure 4.2 shows that the original nozzle sizes of 10,10,10 are the optimum sizes to be used under Hydraulic Horsepower method at a pressure ratio of 1.8 and Jet Impact Force method at a pressure ratio of 0.9. The figure also shows a comparison of the Hydraulic Horsepower and Jet Impact Force methods at an assumed “ m ” value of 1.8. Figure 4.3 is a comparison of the oil field assumption of $m = 1.8$ and calculated $m=1.953$. Figure 4.4 is the comparison of the assumed value of m to the calculated value of m under Jet Impact Force method. These two graphs show that the results of using an assumed value of m is in close agreement with the calculated value of m , even though the value of the calculated m is much more reliable.

Figure 4.5 shows the relationship of the optimum nozzle sizes $d(\text{opt})$ to the pressure ratio under the Hydraulic Horsepower method. Figure 4.6 shows the relationship of the optimum nozzle sizes $d(\text{opt})$ to the pressure ratio under the Jet Impact Force method. The three graphs indicate that as the pressure ratio increases, larger bit nozzles using hydraulic horsepower are needed.

Nozzle Size	Pressure Drop at Bit	Flow Exponent m
11,11,11	0.846	1.949
10,10,10	1.451	1.953
9,10,10	1.653	1.959
9,9,10	1.902	1.964
9,9,9	2.211	1.969
8,9,9	2.556	1.973
8,8,9	2.989	1.977
8,8,8	3.542	1.981

Table 4.1: Flow Exponent Values for Several Bit Nozzle Combinations for HHP

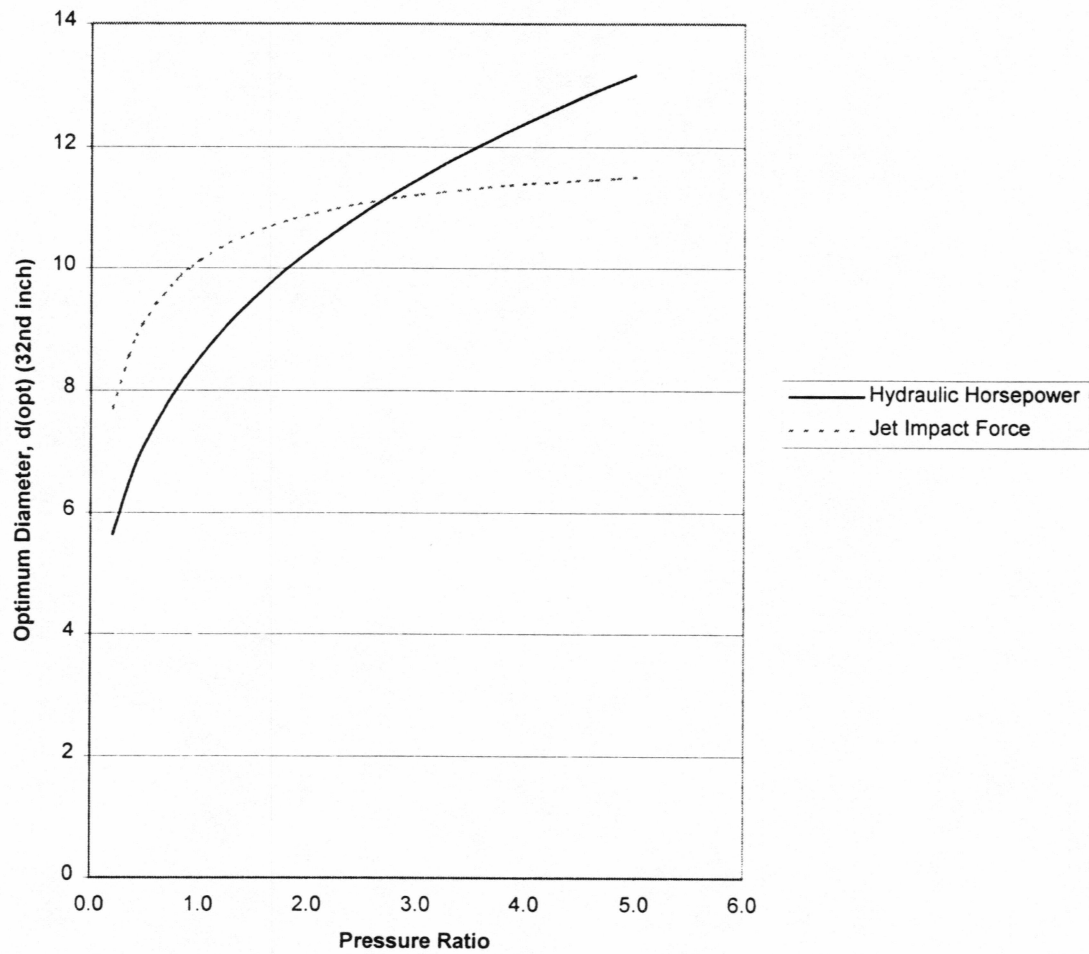


Figure 4.2: Plot of Pressure Ratio vs. Optimum Diameter for HHP and JIF

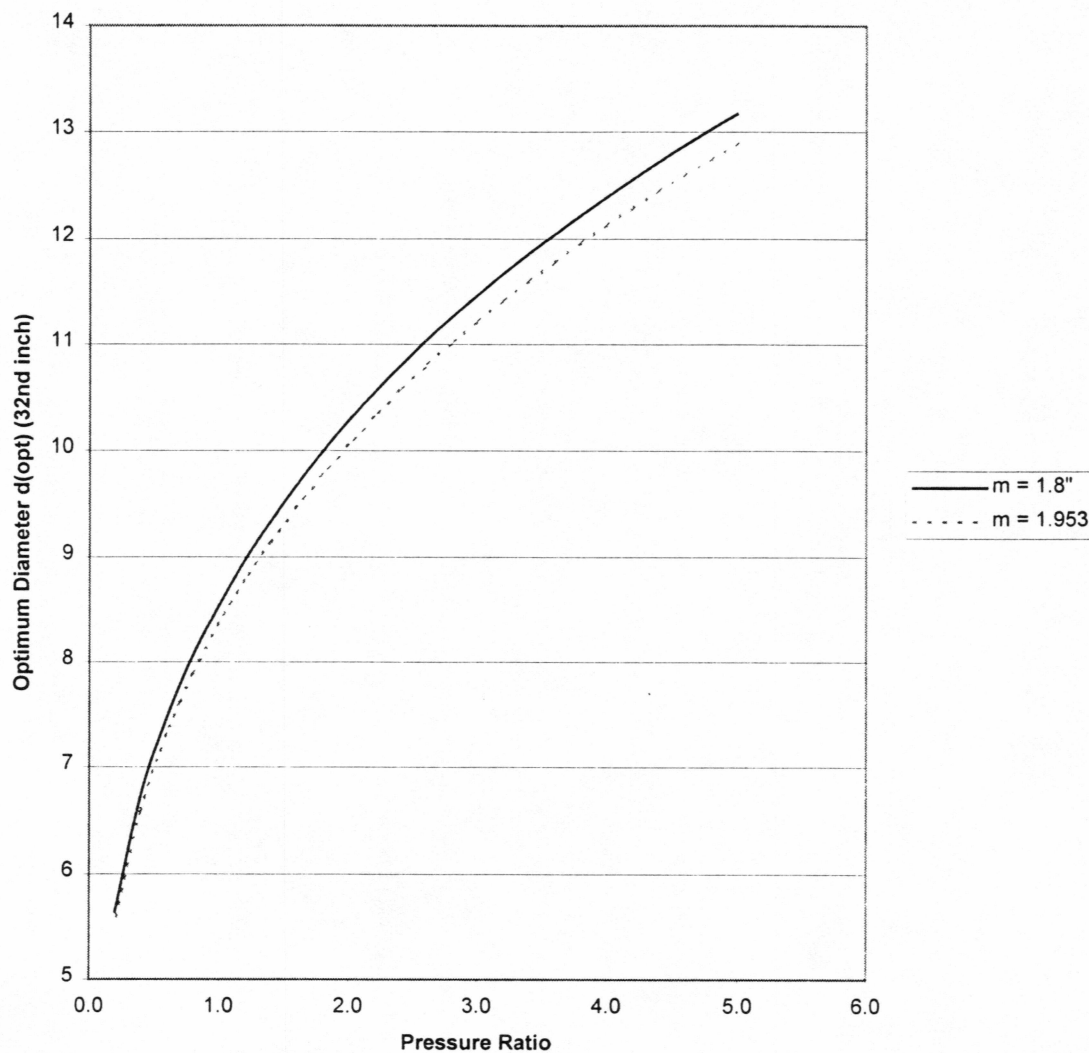


Figure 4.3: Plot of Pressure Ratio vs. Optimum Diameter under Assumed and Calculated Flow Exponent m , for HHP

4.2 Analysis of Extended Nozzles on Rate of Penetration

The concept of extending the nozzles in three cone bits is an old practice. However, the practice is still experimental. Laboratory results by Sutko and Myers² shows that improvements in bottom-hole cleaning have resulted from extended nozzles. Field tests have confirmed the laboratory results. However, it is difficult to prevent the breakage of extended nozzles in field operations; and because of the custom work necessary to create extended nozzles, these nozzles are more expensive.

The economic feasibility of extended nozzles will have to be determined in field operation. However, many investigators conclude that extended nozzles are not feasible. Extended nozzles will increase bottom-hole cleaning and this advantage will have to offset occasional extended nozzle breakage and high bit cost.

4.3 Analysis of Blanked-Off Nozzles on Rate of Penetration

Using one blank nozzle is a common industry practice. The practice was started to prevent the need for very small jets in some hydraulic programs. For example, two 3/8-inch jets are about equal to three 5/16-inch jets and in many cases might be preferable because of the potential plugging of the smaller jets. The question arises whether bottom-hole cleaning will be affected by using two instead of three nozzles.

A study by Sutko and Myers² indicated that bottom-hole cleaning would be improved at constant power levels by reducing the number of nozzles. Field work by Sutko and Myers² has shown improvements in drilling rates, at constant power levels, when using two instead of three bit nozzles. They noted that there have been reports of

overheating in bearings using only one jet and some isolated reports of the same problem using two jets.

In general, there seems to be no disadvantage of using two instead of three nozzles in three cone bits. The largest advantage of using two bit nozzles appears to be a reduction in the danger of plugging when compared to the same area divided among three nozzles.

4.4 Analysis of Hole Size Ratio on Drilling Hydraulics

It was shown in section 4.1 of this chapter that the ratio of the circulating pressure losses to the pressure losses across the bit is a key factor that determines the optimum drilling hydraulic parameter. The effect of annular clearance in drilling hydraulics is very important.

Circulating pressure losses in a system depend on the hole and drillstring geometry. Commonly, in an ideal circulating system, the flow regimes inside the drill pipe and drill collar are most often turbulent, and the flow regimes in the annular area are most likely laminar. The flow regime in the drillstring allows sufficient kinetic energy from the pump to be delivered to the bit nozzles, and the laminar flow in the annulus is to transport the cuttings back to the surface.

A hypothetical oil field condition is adopted to aid in computation for analyzing the ratio of the drill pipe to the hole size, often known as the hole size ratio (α) and defined by equation 4.5:

$$\alpha = d_o / D_1 \quad (4.5)$$

Table 4.2 shows the computed results of pressure ratio at different hole size ratios which is plotted and shown in figure 4.4. The figure shows that for different nozzle sizes, as the hole size ratio decreases, the pressure ratio also decreases. From the results shown in section 4.1, at optimum hydraulic conditions, the pressure ratio of Hydraulic Horsepower method is 1.8 and that of the Jet Impact Force method is 0.9. Figure 4.5 shows that the smaller hole size ratio approaches the optimized hydraulic condition wherein the pressure ratio approach both 1.8 and 0.9 for Hydraulic Horsepower and Jet Impact Force, respectively. Figure 4.4 provides additional information that when a specific bit nozzle is in use, employing the suitable diameter sizes of drill pipe can assist in hydraulic optimization. The smaller hole size ratio favors optimization of drilling hydraulics.

Nozzle Size	12,12,12	12,12,13	13,13,13	14,14,14	14,15,15	15,15,16
Hole Size Ratio α	Pressure ratio $\Delta P_b/\Delta P_c$					
0.367	2.04	1.82	1.48	1.10	0.91	0.76
0.408	3.03	2.70	2.20	1.63	1.35	1.13
0.449	4.01	3.58	2.91	2.16	1.79	1.50
0.49	4.86	4.34	3.53	2.62	2.17	1.82
0.531	5.51	4.92	4.00	2.92	2.46	2.06
0.571	5.95	5.32	4.32	3.21	2.66	2.23

Table 4.2 Hole Size Ratios and Pressure Ratio for HHP

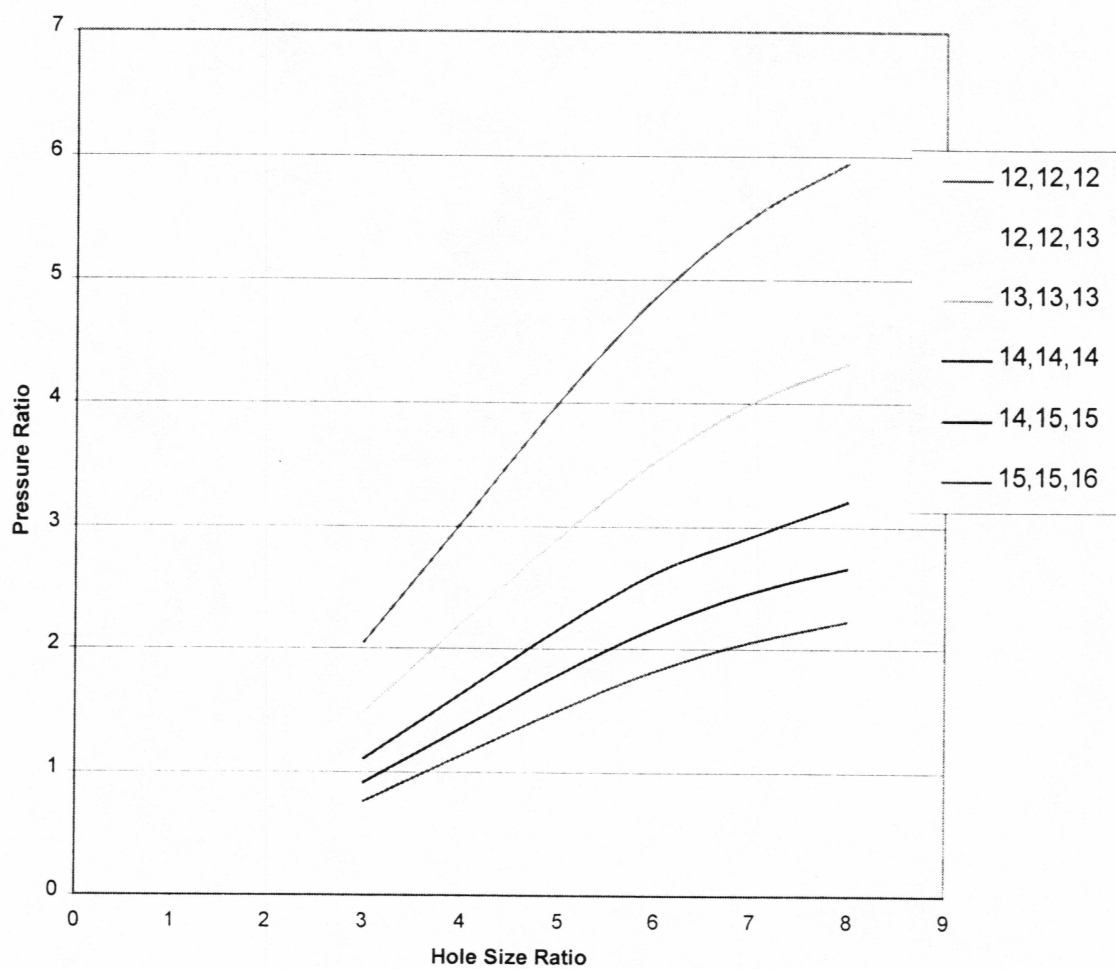


Figure 4.4 Plot of Hole Size Ratio vs. Pressure Ratio for Different Nozzle Sizes using HHP.

Chapter 5

Energy and Maintenance Cost Equations for Mud Pump Operation

5.1 Minimum Cost Drilling: Drilling Company Perspective

The purpose of this section is to show that an optimum hydraulics program can be designed on the basis of minimum drilling costs. Data required for this type of optimization are fuel usage and cost as well as pump maintenance cost. In differential equation form, the drilling cost equation is:

$$\frac{\partial y}{\partial x} = c(x) \quad \text{where } c = \text{cost per foot} \quad (5.1)$$

$$y = \text{cost}$$

$$x = \text{footage}$$

The standard drilling cost equation for determining the cost of drilling a foot of hole is:

$$C_T = \frac{C_B + C_R(T + t)}{F} \quad (5.2)$$

where,

C_T = cost of drilling cost of a foot of hole \$/ft

C_B = bit cost, \$

C_R = rig cost \$/hr

t = rotating time hrs (hours on bottom with one bit)

T = round trip time, hrs

F = Total footage of hole drilled per bit run, ft

According to Rust³, the cost of all maintenance and energy are included in the daily rig rate. Because the cost of maintenance and energy are not directly represented in the standard drilling cost equation, the operator of the well may not consider optimizing energy cost and maintenance cost a priority. However, optimizing these cost would be of great interest to the drilling company. By reducing its own cost, the drilling company will be more competitive with its future bids, thus, indirectly optimizing the operator's cost.

5.2 Cost of Fuel Equation

According to Nelson¹⁵, using a typical specific consumption value of diesel engines of .38 lb/(hp – hr), 80% power transmission efficiency, and 85% pump efficiency, an estimate of hydraulic horsepower output cost of about .04 cents per horsepower hour with diesel fuel cost in 1965 of 18 cents/gal. Therefore, fuel cost to provide the pump hydraulic horsepower can be expressed as:

$$D = (HHP)f = 0.04HHP \quad (5.3)$$

f = output cost per horsepower hour

D = Fuel cost per hour \$/hr

Equation 5.3 presents a problem in that it contains a constant of (.04) which is based on a cost of 18 cents per gallon and again, it was created 35 year ago. A two-step process can bring the constant to represent today's cost.

1. Determine a yearly rate of increase for the price of fuel over the last 35 years, and
2. Use Present Worth Method to correct the .04 constant.

First, to determine the yearly rate of increase (interest rate) the future value is normalized to present value using equation 5.4.

$$(F / P, i\%, N) = (1 + i)^N \quad (5.4)$$

where, F - Future Worth of Money

P - Present Worth of Money

N - number of compounding periods

i - effective interest rate per period

(F/P,i%,N)- Present Worth Factor (PWF)

but,

$$PWF = (1 + i)^N \quad (5.5)$$

solving for i,

$$\ln(PWF) = N \ln(1 + i) \quad (5.6)$$

$$\ln(1 + i) = \frac{\ln(PWF)}{N} \quad (5.7)$$

$$e^{\ln(1+i)} = e^{\frac{\ln(PWF)}{N}} \quad (5.8)$$

$$i = e^{\frac{\ln(PWF)}{N}} - 1 \quad (5.9)$$

Using a current diesel fuel price of \$1.65 per gallon, the present worth factor can be determined.

$$PWF = \frac{Future}{Present} \quad (5.10)$$

$$PWF = \frac{1.65}{.18} = 9.17$$

solving for i ,

$$i = e^{\frac{\ln(9.17)}{35}} - 1 = .0654 \quad (5.11)$$

Over the last 35 years diesel fuel prices have risen almost twice (6.5%) the annual rate of inflation compared to an average rate of inflation of 3.85% (US Census Bureau: Statistical Abstract of the US)¹⁶.

With the annual rate having been determined, the Present Worth in the fuel cost equation can be obtained from;

$$NPW = P\left(\frac{F}{P}, i\%, N\right) \text{ Net Present Worth} \quad (5.12)$$

$$NPW = P\{1 + i\}^N \quad (5.13)$$

$$NPW = .04(1.0654)^{35} = .350 \text{cents}$$

The cost of fuel equation becomes;

$$D = (HHP)f = 0.350HHP \quad (5.14)$$

5.3 Cost of Pump Maintenance Equation

According to the work of Doiron and Deane¹, a relationship for pump parts replacement cost as a function of standpipe pressure over a range of 1500 to 3500 psi. is:

$$P_{pr} = Z \left(\frac{P_{pr}}{P_{st}} \right)^{pq} \quad (5.15)$$

where, $Pq = 1.52$ Constant
 $Z =$ cost per operating hour
 $P_{pr} =$ Pump replacement cost
 $P_{st} = 1500$ psi minimum standpipe pressure

According to Dorion and Deane¹, a rough estimate of the average rig pump replacement cost per operating hour is \$5.00/hr. Because this value is from research done in 1980 by Dorion and Deane¹, a NPW(Net Present Worth) calculation based on inflation over the last 20 years of 3.85%(US Census Bureau: Statistical Abstract of the US)¹⁶ needs to be evaluated.

$$NPW = P(F/P, i\%, N) \quad (5.16)$$

where,

$F =$ Future Worth
 $P =$ Present Worth \$5.00
 $I =$ Interest 3.85%
 $N =$ Number of Periods 20 years

In equation form, this formula is:

$$P(F/P, i\%, N) = P(1+i)^N \quad (5.17)$$

This gives a NPW of:

$$NPW = 5.00(1 + 0.04)^{20} = \$10.96 \quad (5.18)$$

This cost is based on cost of fluid end expendables only and assumes no additional rig down time for more frequent replacement of expendables. It is assumed that pump maintenance can be conducted during normal down time periods such as waiting on cement time.

Doiron and Deane's¹ equation can be expressed in terms of Horsepower, as shown below. The pump hydraulic horsepower is expressed as;

$$HHP = \frac{P_p Q}{1714} \quad (5.19)$$

$$P_p = \frac{1714 HHP}{Q} \quad (5.20)$$

Therefore,

$$P_{pr} = Z \left(\frac{1714 HHP}{1500 Q} \right)^{pq} \text{ \$ /hr} \quad (5.21)$$

The total cost equation for maintenance and fuel is:

$$C_t = 0.350 HHP + 10.96 \left(\frac{1.143 HHP}{Q} \right)^{1.52} \text{ \$ /hr} \quad (5.22)$$

Equation 5.22 can be used to evaluate the total cost for either hydraulic optimization technique as a function of fuel, and pump maintenance cost.

Chapter 6

Economic Evaluation

6.1 Discussion of The Cost Comparison

In this section, an example problem is presented and a cost comparison for Jet Impact Force and Hydraulic Horsepower is shown. Using equations that are presented in chapters 4 and 5, a cost comparison between operating the mud pump for maximum optimized jet impact force and hydraulic horsepower is presented. An assumption is made in the example problem that the motor is directly driving the mud pump and that no generator or DC current is being supplied.

6.2 Example Problem

Given a well drilled to 11,200 feet with a 12 inch bit that has 3 nozzles of 16/32 inch each. The drill string was made up of 10,600 feet drill pipe, 5-1/2 inch O.D. and 4.35 inch I.D. and drill collars of 600 feet. 10 inch O.D. and 3 inch I.D. The mud used had the following properties:

MW = 11.8 ppg Pump, Pressure at 462 gpm = 1800 psi.

The pump was slowed down and additional pressure measurements were made as follows:

300 gpm at $P_p = 850$ psi

200 gpm at $P_p = 430$ psi

Solution:

Assuming the next bit run lasts 8 hours, determine the Mud pump cost for;

(a) Jet Impact Force

(b) Bit Hydraulic Horsepower

From equation 3.21,
$$\Delta P_b = \frac{17.3 \rho q^2}{d_{av}^4} \quad (3.21)$$

At 462 gpm
$$\Delta P_b = \frac{17.3(11.8)((462)^2)}{16^4} = 665 \text{ psi}$$

At 300 gpm
$$\Delta P_2 = 280 \text{ psi} \quad \text{using equation 3.21}$$

At 200 gpm
$$\Delta P_3 = 125 \text{ psi} \quad \text{using equation 3.21}$$

Where ΔP_2 and ΔP_3 are the change in bit pressure at 300 and 200 gpm, respectively.

and,
$$\begin{aligned} \Delta P_{c1} &= 1800 - 665 = 1135 \text{ psi} \\ \Delta P_{c2} &= 850 - 280 = 570 \text{ psi} \\ \Delta P_{c3} &= 430 - 125 = 305 \text{ psi} \end{aligned}$$

The value of m is obtained as:

$$m = \frac{\log 1135 - \log 570}{\log 462 - \log 300} = 1.59 \quad (4.4)$$

Jet Impact force:

From equation:

$$\Delta P_c = \frac{2}{m+2} P_p = \left(\frac{2}{3.59}\right) 1800 = 1003 \text{ psi} \quad (3.34)$$

$$\Delta P_{bopt} = 1800 - 1003 = 797 \text{ psi} \quad (3.33)$$

$$q_{opt} = \left(\frac{P_{opt}}{P_s} \right)^{1/2} q = 427 \text{ gpm} \quad (3.36)$$

Hydraulic Horsepower:

From equation:

$$\Delta P_{copt} = \frac{1}{m+1} P_p = \left(\frac{1}{2.59} \right) 1800 = 695 \text{ psi} \quad (3.18)$$

$$\Delta P_{bopt} = 1800 - 1003 = 797 \text{ psi} \quad (3.19)$$

$$q_{opt} = \left(\frac{P_{opt}}{P_s} \right)^{1/2} q = 427 \text{ gpm} \quad (3.36)$$

Recalling equation 3.9;

$$\text{HHP} = (q_{opt})(\Delta P_{bopt})/1714 \quad (3.9)$$

Substituting the values of q_{opt} and ΔP_{bopt} , data of table 6.1 are obtained.

Cost Comparison between JIF and HHP:

	$q_{(opt)}$ gpm	$\Delta P_{c(opt)}$ psi	$\Delta P_{b(opt)}$ psi	HP hp	1 hour Operational Cost C_t \$	8 hour Operational Cost C_t \$
JIF	427	1003	797	199	\$47.72	#381.73
HHP	339	695	1105	219	\$54.71	\$437.68
Difference					\$6.99	\$55.95

Table 6.1: Calculated Operating Cost for HHP and JIF.

The total costs was calculated using equation 5.22.

$$C_t = 0.350HHP + 10.96 \left(\frac{1.143HHP}{Q} \right)^{1.52} \text{ $/hr} \quad (5.22)$$

To find the cost for one hour of operation optimizing for JIF, the following shows result using equation 5.22:

$$C_t = 0.350 \times 199 + 10.96 \left(\frac{1.143 \times 199}{427} \right)^{1.52} = \$47.72 \quad (5.22)$$

This table is based on a fuel cost of \$1.65 per gallon. If it is assumed that the value of m does not change, the effect of increasing the standpipe pressure and how it

changes the comparison between the two different methods can be noticed. Table 6.1 shows how the change in standpipe pressure affects several different variables, and ultimately, the cost comparison. Figure 6.1 gives a graphical representation of the data.

Figures 6.2 through 6.8 show the effect of change in m and standpipe pressure values and how they relate to costs of optimization using hydraulic horsepower and jet impact force. Tabular data similar to figures 6.2 through 6.8 are shown in tables D2 through D8 of the appendix.

It is quite noticeable that the difference in cost between JIF and HHP widens as the standpipe pressure requirement increase. At higher pressures, the HHP method costs rise at steeper rate than do the costs for JIF. This is of great interest in coiled tubing drilling. In coiled tubing drilling, standpipe pressure rarely drops below 3000 psi. Also, the small working space mandates the smallest available generators and/or engine. The greater flow rate requirements may have an impact on mud pump size and drive requirements.

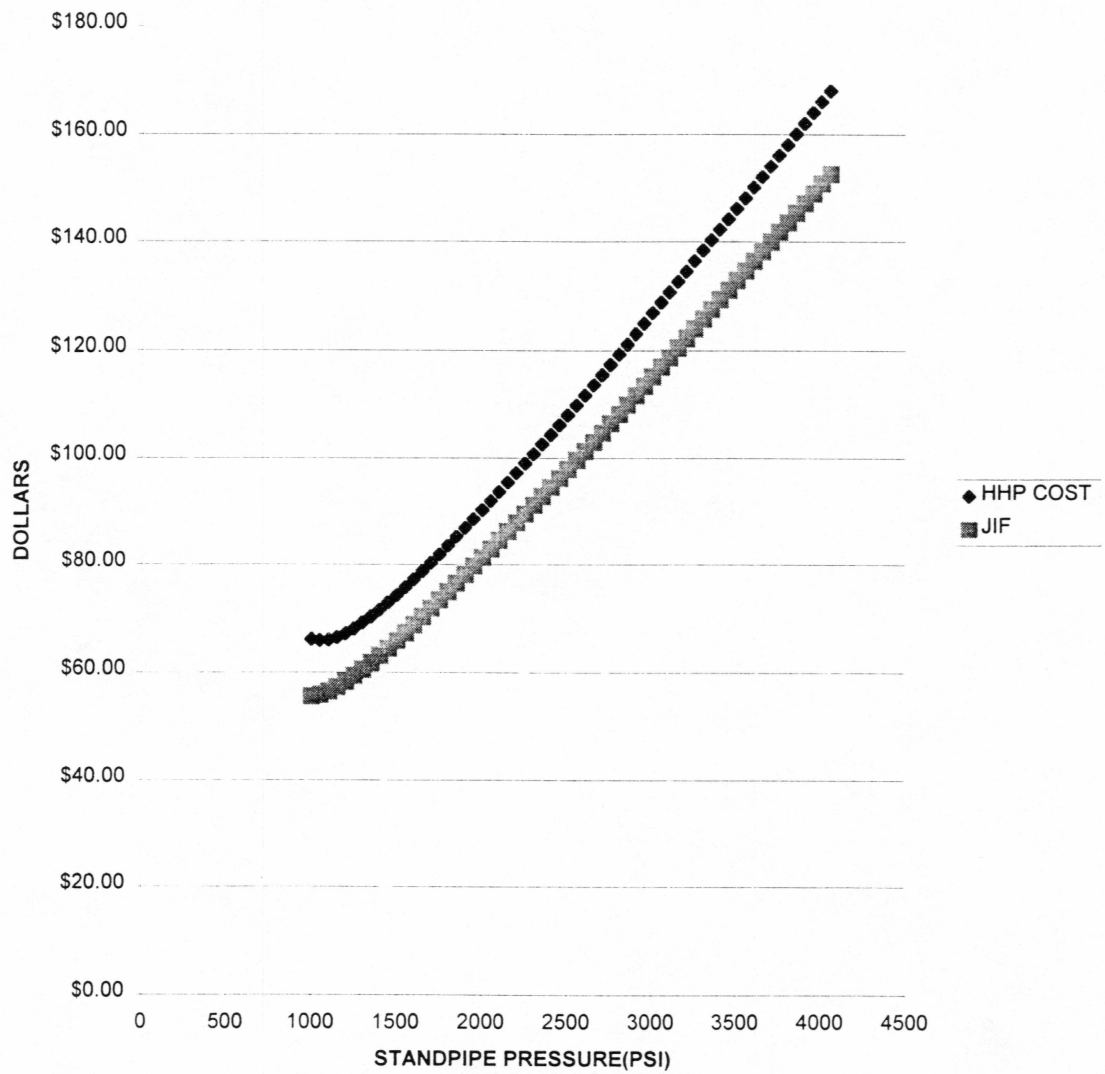


Figure 6.1: Plot of JIF vs. HHP for $m = 1.59$

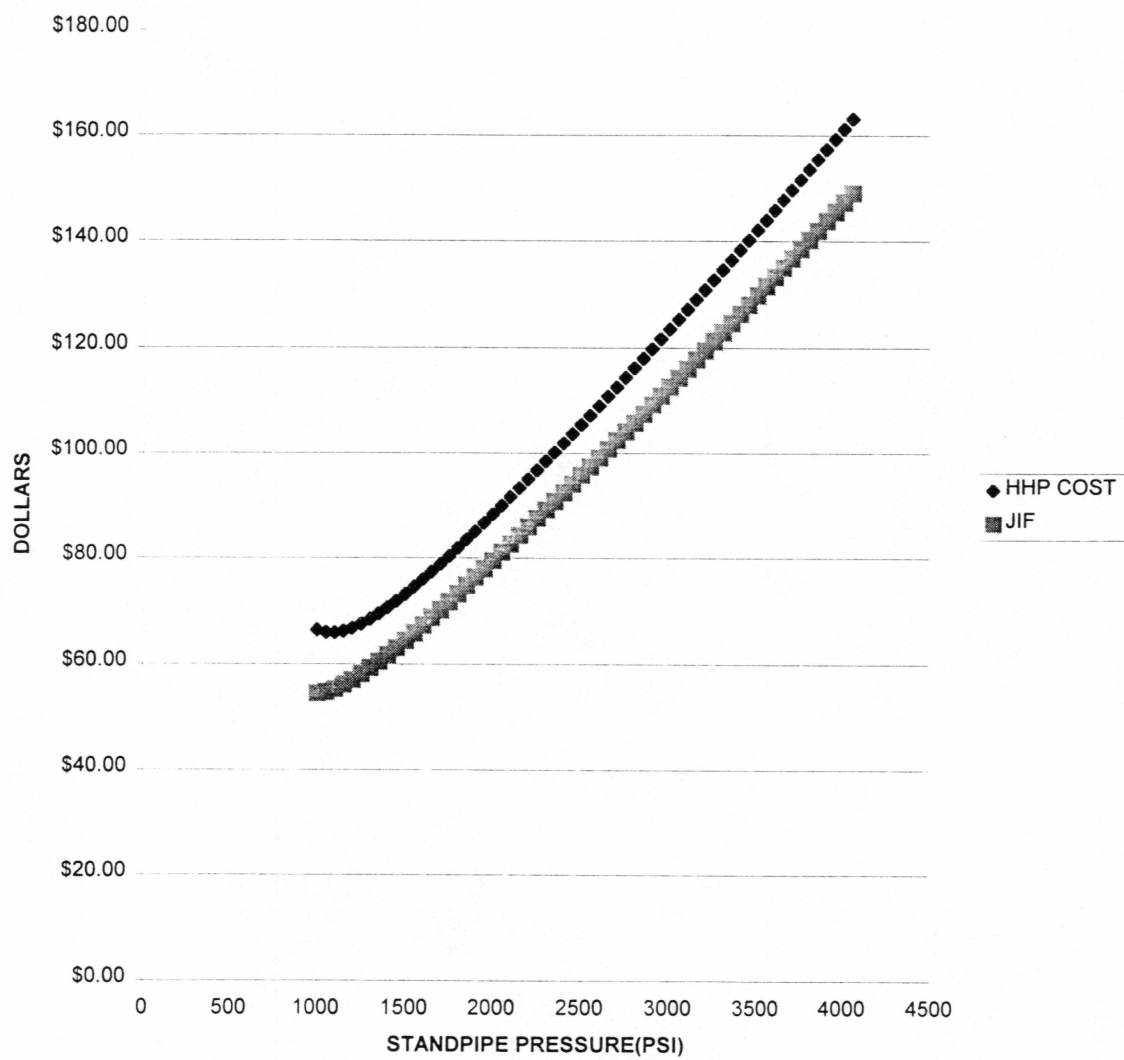


Figure 6.2: Plot of JIF vs. HHP $m = 1.50$

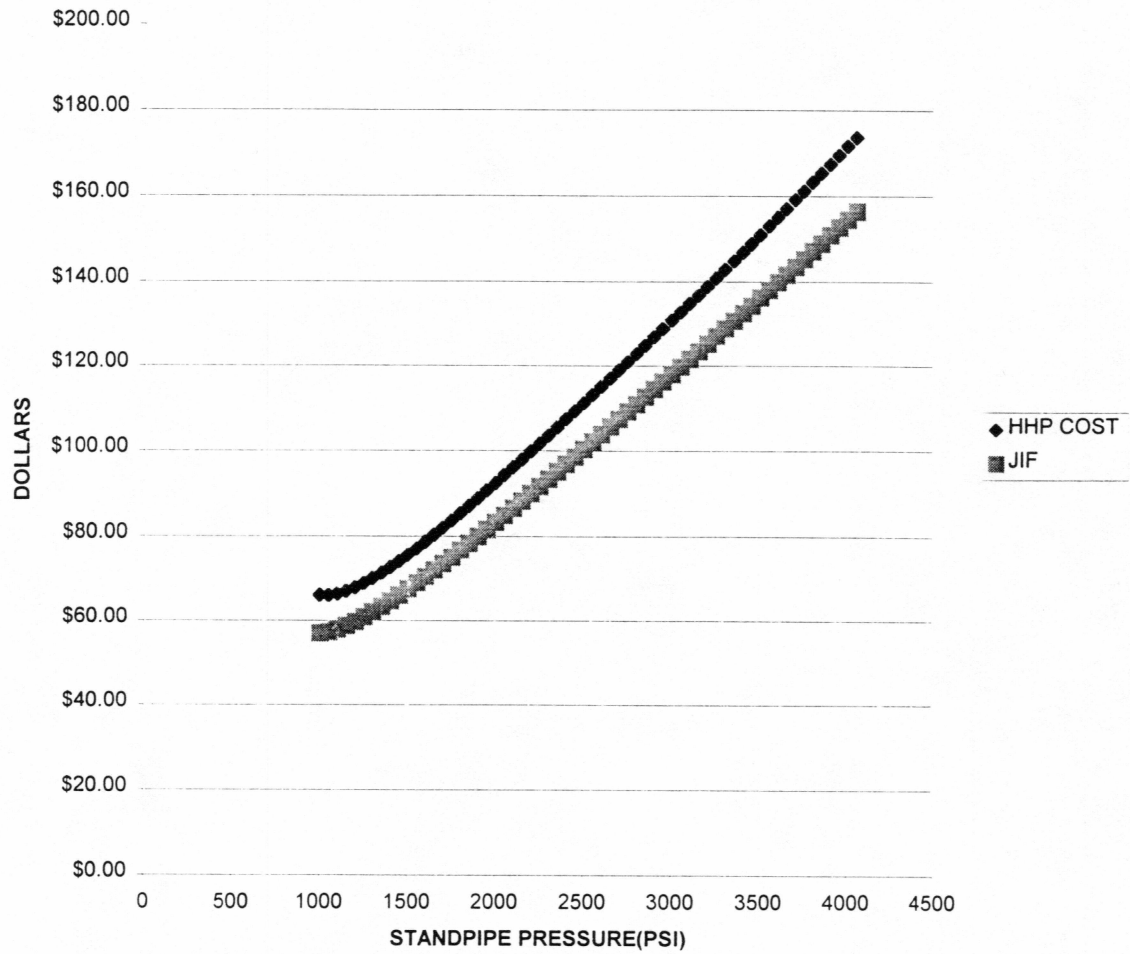


Figure 6.3: Plot of JIF vs. HHP for $m=1.70$

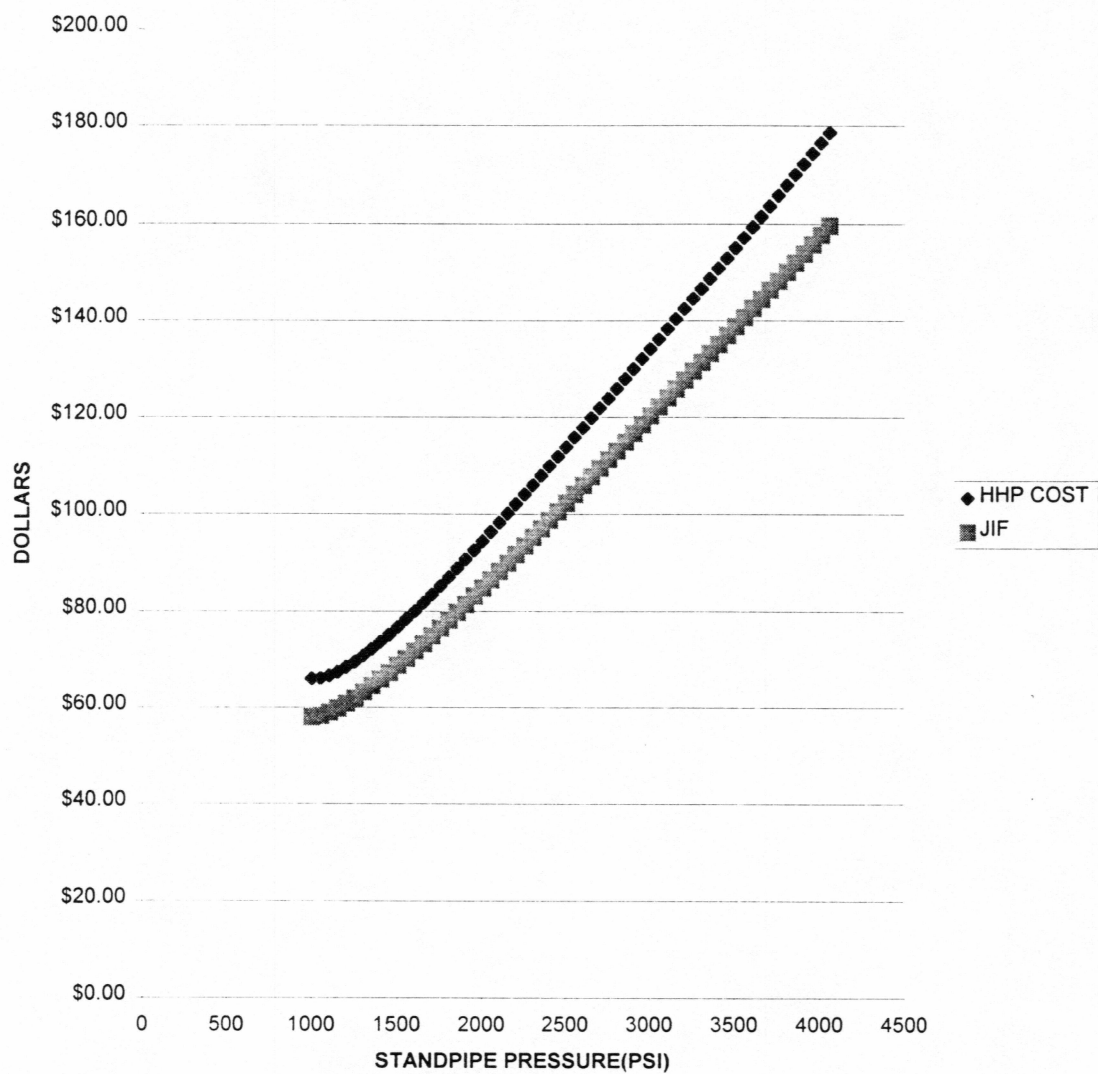


Figure 6.4: Plot of JIF vs. HHP for $m=1.80$

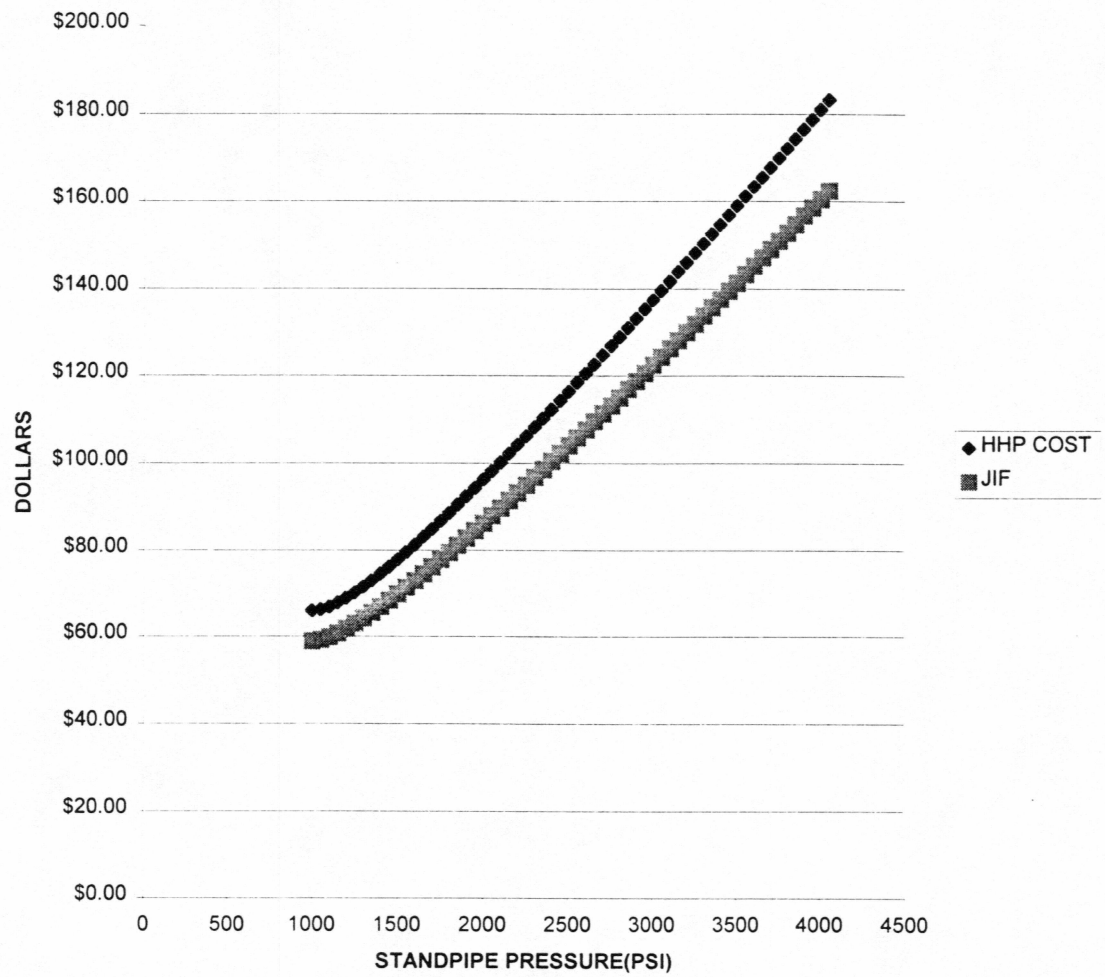


Figure 6.5: Plot of JIF vs. HHP for $m=1.90$

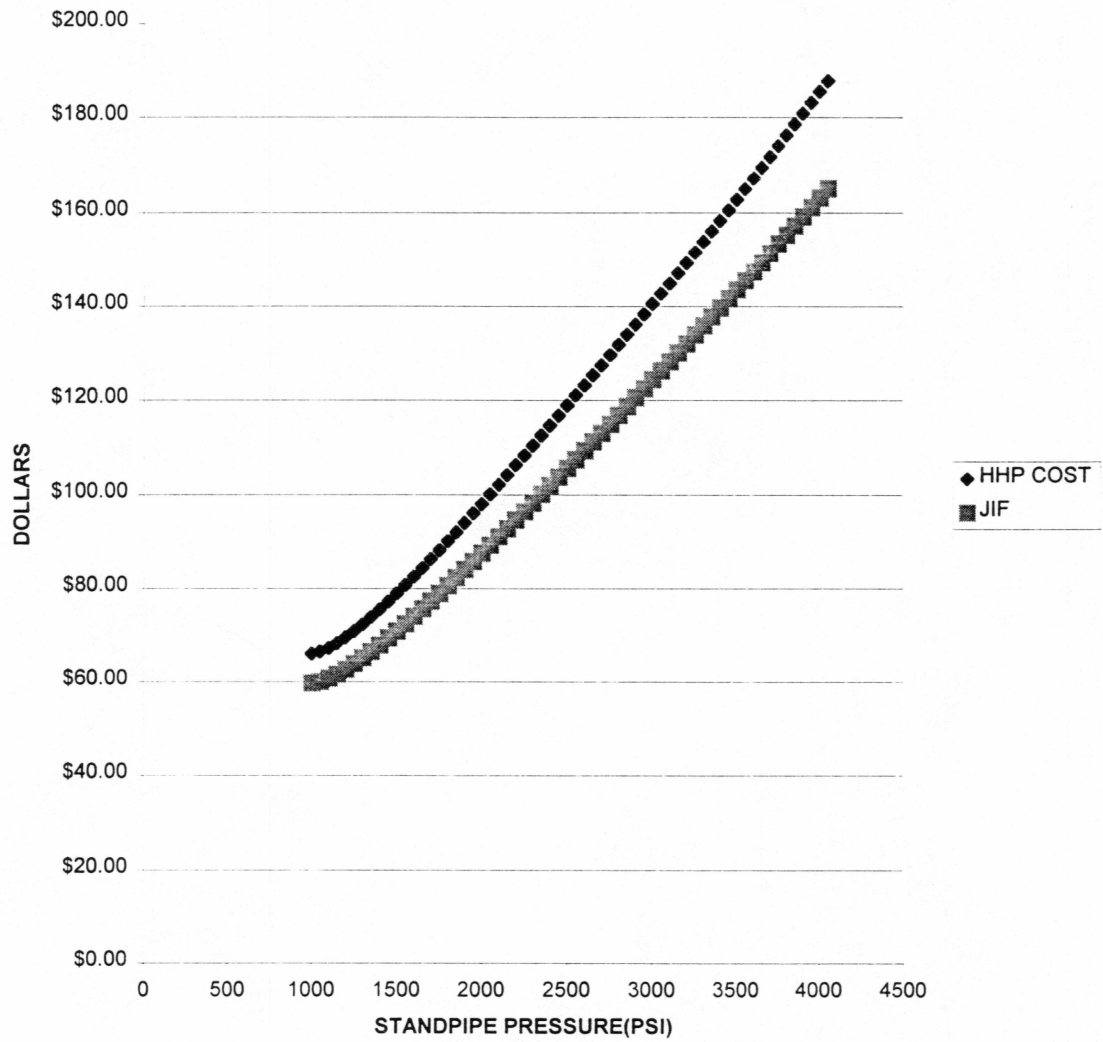


Figure 6.6: Plot of JIF vs. HHP for $m=2.00$

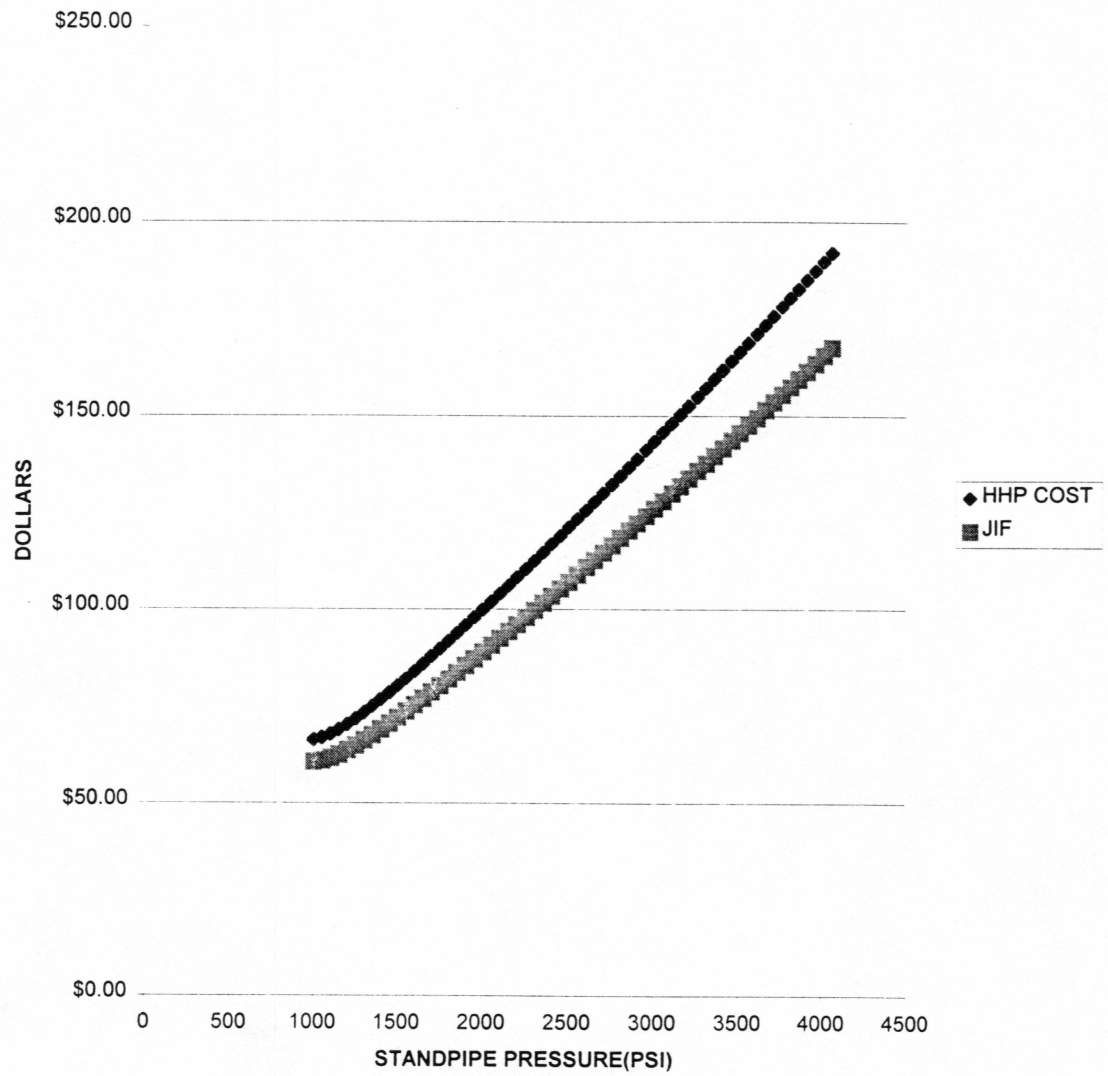


Figure 6.7: Plot of JIF vs. HHP for $m=2.10$

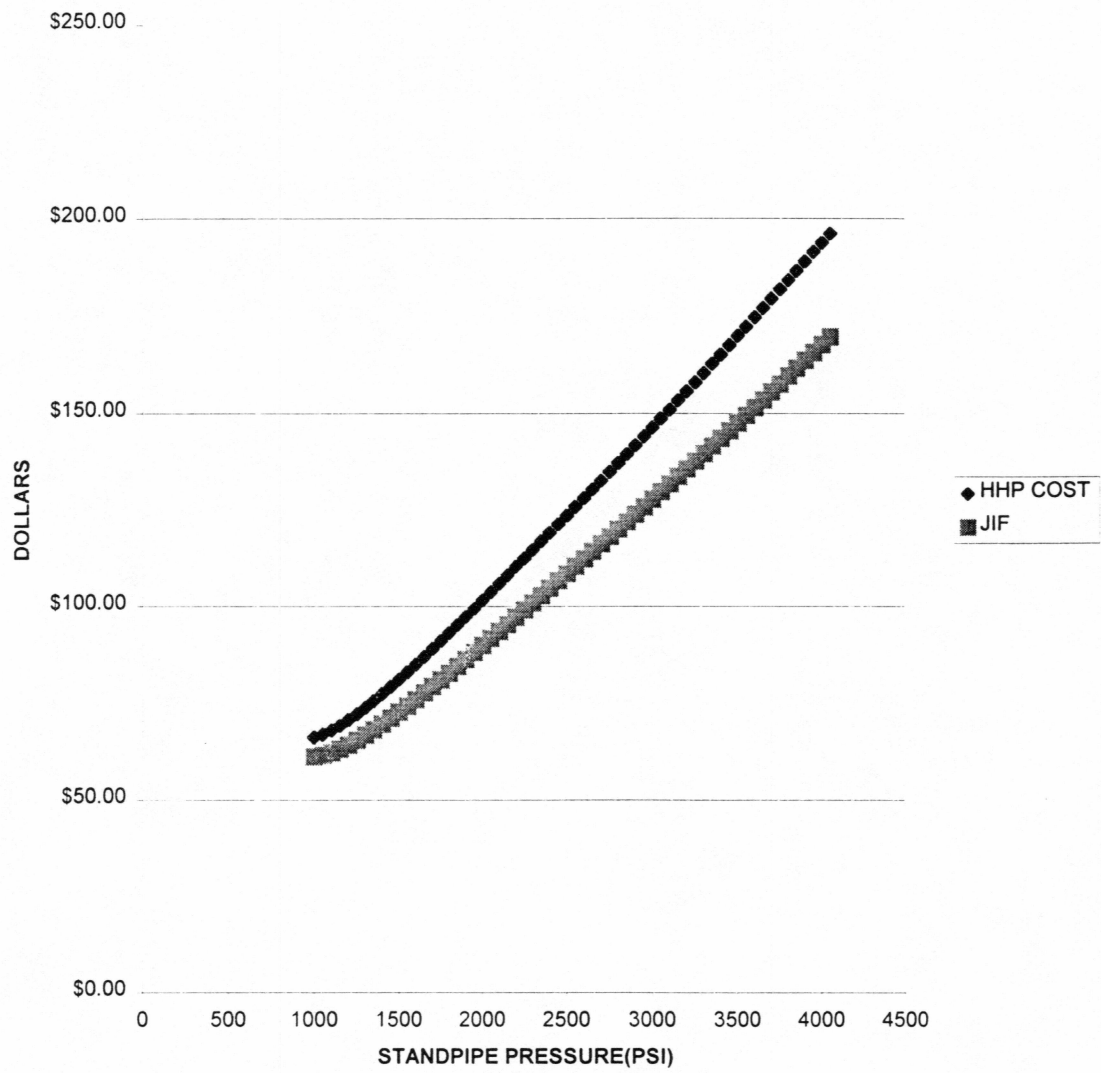


Figure 6.8: Plot of JIF vs. HHP for $m=2.20$

Chapter 7

Conclusions and Recommendations

This study showed that optimum hydraulic programs can be designed on the basis of minimum drilling cost. Data required for this type of optimization are fuel and pump maintenance hourly costs. Even though the operator of the well may not realize the savings from the proposed program directly, but over a period of time, may realize indirectly from more competitive bid proposals submitted by the drilling company who is trying to optimize pump maintenance and fuel cost.

7.1 Conclusions:

The conclusions of this study are summarized as follows:

1. Under similar drilling conditions, Optimizing for JIF is more cost effective than optimizing for HHP.
2. The example problem shows an expected savings of about \$6.99 per hour of Mud Pump Operation.
3. The study shows that for m values greater than 1.8 the cost savings optimizing for JIF versus HHP are greater.
4. The study shows that for m values less than 1.6 the cost to optimize for JIF and HHP are equal.

7.2 Recommendations:

Given that some rigs cost as much as thirty five thousand dollars (\$35,000.00) per day to operate, savings of \$6.99 will not be given any real consideration. Using these data to convince an operating companies drilling engineer to change his drilling optimization program from HHP to JIF would not be prudent. However, what may be a concern is the possible need for larger pieces of equipment, which may cause great problems for a small coiled tubing drilling rig.

Chapter 8

NOMENCLATURE

A_n	=	Cross sectional area of the nozzle, in ²
C_b	=	Bit cost, \$
C_d	=	Drag coefficient.
C_r	=	Rig cost, \$
C_t	=	Cost per foot, \$/ft.
D	=	Mud pump fuel cost
d_c	=	Nozzle equivalent diameter, in.
d_s	=	Solid diameter, in.
D_i	=	Inner diameter of the hole, in.
d_i	=	Inner diameter of the drillstrings, in.
d_o	=	Outer diameter of the drillstring, in.
$d(\text{opt})$	=	Optimum nozzle diameter, in.
g	=	Gravitational acceleration.
f	=	Output cost per horsepower, \$/hp
F	=	Future Worth of Money, \$
F_j, JIF	=	Jet impact force, lb _f
HHP	=	Hydraulic horsepower, hp.
i	=	Effective interest rate, %
k	=	Power-law consistency index,

$$lb_f - \text{sec}''/100 ft^2.$$

K_1	=	Constant representing $\sqrt{\frac{1120}{\rho_m}}$.
K_2	=	Constant representing $\frac{\rho_m k_1}{60g}$.
K'	=	Mud weight and wellbore constant
L	=	Drillpipe length, ft.
m	=	Parasitic pressure loss exponent.
n	=	Power-law fluid flow index.
N	=	Number of compounding periods
NPW	=	Net Present Worth,\$
N_{rp}	=	Particle Reynolds Number.
P	=	Present Worth of Money,\$
ΔP_a	=	Pressure loss at the annulus, psi.
ΔP_b	=	Pressure drop across the bit, psi.
$\Delta P_b(\text{opt})$	=	Optimum pressure drop across the bit, psi.
ΔP_c	=	Circulating pressure loss,psi.
$\Delta P_c(\text{opt})$	=	Optimum circulating pressure loss, psi.
ΔP_{dca}	=	Pressure loss at the drill collar annulus, psi.
ΔP_{dcin}	=	Pressure loss inside the drill collar,psi.
ΔP_{dpa}	=	Pressure loss at the drillpipe annulus, psi.
ΔP_{dpin}	=	Pressure loss inside the drillpipe, psi

P_p	=	Pump pressure, psi.
ΔP_{sc}	=	Pressure loss due to surface connection, psi.
ΔP_{sys}	=	System pressure loss, psi.
PWF	=	Present Worth Factor, \$
t	=	Rotating time, t.
T	=	Round trip time, hrs.
Q	=	Volumetric flowrate of drilling fluid, gpm.
$Q_{(opt)}$	=	Optimum flowrate of drilling fluid, gpm.
V	=	Velocity of drilling fluid in drillstrings, fpm.
V_a	=	Annular velocity of drilling fluid, fpm.
α	=	Ratio of hole size to drillstring

Chapter 9

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APPENDIX

<i>Nozzle (32nd inch)</i>	<i>Equivalent Diameters</i> <i>inch</i>
3 nozzle bit	
<i>10,10,10</i>	<i>0.5413</i>
<i>9,10,10</i>	<i>0.5238</i>
<i>9,9,10</i>	<i>0.5058</i>
<i>9,9,9</i>	<i>0.4871</i>
<i>8,9,9</i>	<i>0.4698</i>
<i>8,8,9</i>	<i>0.4518</i>
<i>8,8,8</i>	<i>0.433</i>
2 nozzle bit	
<i>10,10</i>	<i>0.4419</i>
<i>9,10</i>	<i>0.4204</i>
<i>9,9</i>	<i>0.3977</i>
<i>8,9</i>	<i>0.3763</i>
<i>8,8</i>	<i>0.3536</i>

Table A-1 Nozzle Sizes and Equivalent Diameters Two and Three
Nozzle Bits

P_b/P_c	P_b	P_c	P_p	$P_c(opt)$	$P_b(opt)$	K'	$Q(opt)$	$d(opt)$
5.0	1.451	0.290	1.741	0.622	1.119	0.00460	15.27	13.17
4.8	1.451	0.302	1.753	0.626	1.127	0.00479	14.99	13.03
4.6	1.451	0.315	1.766	0.631	1.135	0.00500	14.70	12.88
4.4	1.451	0.330	1.781	0.636	1.145	0.00523	14.40	12.72
4.2	1.451	0.345	1.796	0.642	1.155	0.00547	14.10	12.56
4.0	1.451	0.363	1.814	0.648	1.166	0.00575	13.80	12.39
3.8	1.451	0.382	1.833	0.654	1.178	0.00605	13.49	12.22
3.6	1.451	0.403	1.854	0.662	1.192	0.00639	13.18	12.04
3.4	1.451	0.427	1.878	0.671	1.207	0.00676	12.85	11.86
3.2	1.451	0.453	1.904	0.68	1.224	0.00719	12.53	11.67
3.0	1.451	0.484	1.934	0.691	1.244	0.00766	12.19	11.46
2.8	1.451	0.518	1.969	0.703	1.266	0.00821	11.85	11.25
2.6	1.451	0.558	2.009	0.717	1.291	0.00884	11.50	11.03
2.4	1.451	0.605	2.055	0.734	1.321	0.00958	11.14	10.79
2.2	1.451	0.659	2.110	0.754	1.357	0.01045	10.77	10.54
2.0	1.451	0.725	2.176	0.777	1.399	0.01150	10.39	10.28
1.8	1.451	0.806	2.257	0.806	1.451	0.01277	10.00	9.99
1.6	1.451	0.907	2.358	0.842	1.516	0.01437	9.60	9.68
1.4	1.451	1.036	2.487	0.888	1.599	0.01642	9.18	9.34
1.2	1.451	1.209	2.660	0.95	1.710	0.01916	8.75	8.97
1.0	1.451	1.451	2.902	1.036	1.865	0.02299	8.30	8.54
0.8	1.451	1.814	3.264	1.116	2.098	0.02874	7.82	8.06
0.6	1.451	2.418	3.869	1.382	2.487	0.03883	7.33	7.47
0.4	1.451	3.627	5.078	1.814	3.264	0.05748	6.80	6.73
0.2	1.451	7.254	8.705	3.109	5.596	0.11497	6.25	5.63

Table B-1 Optimization Results for Hydraulic Horsepower Method (10 gpm
Nozzle Sizes 10,10,10, m=1.8)

P_b/P_c	P_b	P_c	P_p	$P_c(opt)$	$P_b(opt)$	K'	$Q(opt)$	$d(opt)$
5.0	144.5	28.89	173.35	61.911	111.441	0.00726	152.72	13.19
4.8	144.5	30.10	174.56	62.341	112.214	0.00756	149.87	13.04
4.6	144.5	31.40	175.86	62.809	113.056	0.00789	146.97	12.89
4.4	144.5	32.83	177.29	63.319	113.973	0.00825	144.03	12.73
4.2	144.5	34.40	178.86	63.877	114.978	0.00864	141.05	12.57
4.0	144.5	36.12	180.58	64.491	116.084	0.00907	138.01	12.41
3.8	144.5	38.02	182.48	65.170	117.306	0.00955	134.91	12.24
3.6	144.5	40.13	184.59	65.924	118.664	0.01008	131.76	12.06
3.4	144.5	42.49	186.95	66.767	120.181	0.01067	128.54	11.87
3.2	144.5	45.14	189.60	67.716	121.888	0.01134	125.26	11.68
3.0	144.5	48.15	192.61	68.790	123.823	0.01210	121.91	11.48
2.8	144.5	51.59	196.05	70.019	126.034	0.01296	118.49	11.26
2.6	144.5	55.56	200.02	71.436	128.585	0.01396	114.98	11.04
2.4	144.5	60.19	204.65	73.090	131.562	0.01512	111.39	10.80
2.2	144.5	65.66	210.12	75.044	135.079	0.01649	107.70	10.55
2.0	144.5	72.23	216.69	77.389	139.301	0.01814	103.91	10.29
1.8	144.5	80.26	224.72	80.256	144.460	0.02016	100.00	10.00
1.6	144.5	90.29	234.75	83.838	150.909	0.02268	95.97	9.69
1.4	144.5	103.19	247.65	88.445	159.201	0.02592	91.79	9.35
1.2	144.5	120.38	264.84	94.587	170.256	0.03024	87.46	8.98
1.0	144.5	144.46	288.92	103.186	185.734	0.03629	82.95	8.55
0.8	144.5	180.58	325.04	116.084	208.951	0.04536	78.23	8.07
0.6	144.5	240.77	385.23	137.581	247.646	0.06048	73.28	7.48
0.4	144.5	361.15	505.61	180.575	325.035	0.09072	68.04	6.73
0.2	144.5	722.30	866.76	309.557	557.203	0.18143	62.46	5.64

Table B-2 Optimization Results for Hydraulic Horsepower Method (100 gpm
Nozzle Sizes 10,10,10, m=1.8)

P_b/P_c	P_b	P_c	P_p	$P_c(opt)$	$P_b(opt)$	K'	$Q(opt)$	$d(opt)$
5.0	1.451	0.290	1.741	0.916	0.825	0.01452	10.00	11.50
4.8	1.451	0.302	1.753	0.923	0.830	0.01462	10.00	11.48
4.6	1.451	0.315	1.766	0.93	0.837	0.01473	10.00	11.46
4.4	1.451	0.330	1.781	0.937	0.843	0.01485	10.00	11.44
4.2	1.451	0.345	1.796	0.945	0.851	0.01498	10.00	11.41
4.0	1.451	0.363	1.814	0.954	0.859	0.01513	10.00	11.39
3.8	1.451	0.382	1.833	0.965	0.868	0.01529	10.00	11.36
3.6	1.451	0.403	1.854	0.976	0.878	0.01546	10.00	11.33
3.4	1.451	0.427	1.878	0.988	0.889	0.01566	10.00	11.29
3.2	1.451	0.453	1.904	1.002	0.902	0.01588	10.00	11.25
3.0	1.451	0.484	1.934	1.018	0.916	0.01614	10.00	11.21
2.8	1.451	0.518	1.969	1.036	0.933	0.01642	10.00	11.16
2.6	1.451	0.558	2.009	1.057	0.952	0.01676	10.00	11.10
2.4	1.451	0.605	2.055	1.082	0.974	0.01714	10.00	11.04
2.2	1.451	0.659	2.110	1.111	1.000	0.01760	10.00	10.96
2.0	1.451	0.725	2.176	1.145	1.031	0.01815	10.00	10.88
1.8	1.451	0.806	2.257	1.188	1.069	0.01883	10.00	10.78
1.6	1.451	0.907	2.358	1.241	1.117	0.01967	10.00	10.66
1.4	1.451	1.036	2.487	1.309	1.178	0.02075	10.00	10.52
1.2	1.451	1.209	2.660	1.4	1.260	0.02219	10.00	10.35
1.0	1.451	1.451	2.902	1.527	1.374	0.02420	10.00	10.13
0.9	1.451	1.612	3.063	1.612	1.451	0.02555	10.00	9.99
0.8	1.451	1.814	3.264	1.718	1.546	0.02723	10.00	9.83
0.6	1.451	2.418	3.869	2.036	1.833	0.03227	10.00	9.42
0.4	1.451	3.627	5.078	2.673	2.405	0.04424	10.00	8.80
0.2	1.451	7.254	8.705	4.581	4.123	0.07261	10.00	7.69

Table B-3 Optimization Results for Jet Impact Force Method (10 gpm
Nozzle Sizes 10,10,10, m=1.8)

P_b/P_c	P_b	P_c	P_p	$P_c(opt)$	$P_b(opt)$	K'	$Q(opt)$	$d(opt)$
5.0	144.5	28.89	173.35	91.238	82.144	0.02292	100.00	11.52
4.8	144.5	30.10	174.56	91.871	82.684	0.02308	100.00	11.50
4.6	144.5	31.40	175.86	92.560	83.304	0.02325	100.00	11.48
4.4	144.5	32.83	177.29	93.311	83.980	0.02344	100.00	11.45
4.2	144.5	34.40	178.86	94.134	84.721	0.02365	100.00	11.43
4.0	144.5	36.12	180.58	95.039	85.536	0.02387	100.00	11.40
3.8	144.5	38.02	182.48	96.040	86.436	0.02412	100.00	11.37
3.6	144.5	40.13	184.59	97.151	87.436	0.02440	100.00	11.34
3.4	144.5	42.49	186.95	98.394	88.554	0.02472	100.00	11.30
3.2	144.5	45.14	189.60	99.791	89.812	0.02507	100.00	11.26
3.0	144.5	48.15	192.61	101.375	91.238	0.02546	100.00	11.22
2.8	144.5	51.59	196.05	103.186	92.867	0.02592	100.00	11.17
2.6	144.5	55.56	200.02	105.274	94.747	0.02644	100.00	11.11
2.4	144.5	60.19	204.65	107.711	96.940	0.02706	100.00	11.05
2.2	144.5	65.66	210.12	110.591	99.532	0.02778	100.00	10.98
2.0	144.5	72.23	216.69	114.047	102.643	0.02865	100.00	10.89
1.8	144.5	80.26	224.72	118.271	106.444	0.02971	100.00	10.79
1.6	144.5	90.29	234.75	123.551	111.196	0.03103	100.00	10.68
1.4	144.5	103.19	247.65	130.340	117.306	0.03274	100.00	10.53
1.2	144.5	120.38	264.84	139.391	125.452	0.03501	100.00	10.36
1.0	144.5	144.46	288.92	152.063	136.857	0.03820	100.00	10.14
0.9	144.5	160.51	304.97	160.511	144.460	0.04032	100.00	10.00
0.8	144.5	180.58	325.04	171.071	153.964	0.04297	100.00	9.84
0.6	144.5	240.77	385.23	202.751	182.476	0.05093	100.00	9.43
0.4	144.5	361.15	505.61	266.111	239.499	0.06684	100.00	8.81
0.2	144.5	722.30	866.76	456.189	410.571	0.11146	100.00	7.70

Table B-4 Optimization Results for Jet Impact Force Method (100 gpm
Nozzle Sizes 10,10,10, m=1.8)

P_b/P_c	P_b	P_c	P_p	$P_c(opt)$	$P_b(opt)$	K'	$Q(opt)$	$d(opt)$
5.0	1.451	0.290	1.741	0.590	1.151	0.00460	14.83	12.89
4.8	1.451	0.302	1.753	0.594	1.159	0.00479	14.55	12.74
4.6	1.451	0.315	1.766	0.598	1.168	0.00500	14.27	12.60
4.4	1.451	0.330	1.781	0.603	1.178	0.00523	13.98	12.45
4.2	1.451	0.345	1.796	0.608	1.188	0.00547	13.69	12.29
4.0	1.451	0.363	1.814	0.614	1.199	0.00575	13.40	12.13
3.8	1.451	0.382	1.833	0.621	1.212	0.00605	13.10	11.96
3.6	1.451	0.403	1.854	0.628	1.226	0.00639	12.79	11.78
3.4	1.451	0.427	1.878	0.636	1.242	0.00676	12.48	11.60
3.2	1.451	0.453	1.904	0.645	1.259	0.00719	12.16	11.41
3.0	1.451	0.484	1.934	0.655	1.279	0.00766	11.84	11.21
2.8	1.451	0.518	1.969	0.667	1.302	0.00821	11.50	11.01
2.6	1.451	0.558	2.009	0.680	1.329	0.00884	11.16	10.79
2.4	1.451	0.605	2.055	0.696	1.359	0.00958	10.81	10.56
2.2	1.451	0.659	2.110	0.715	1.396	0.01045	10.46	10.31
2.0	1.451	0.725	2.176	0.737	1.439	0.01150	10.09	10.05
1.8	1.451	0.806	2.257	0.764	1.493	0.01277	9.71	9.77
1.6	1.451	0.907	2.358	0.798	1.559	0.01437	9.32	9.47
1.4	1.451	1.036	2.487	0.842	1.645	0.01642	8.91	9.14
1.2	1.451	1.209	2.660	0.901	1.759	0.01916	8.49	8.77
1.0	1.451	1.451	2.902	0.983	1.919	0.02299	8.05	8.36
0.8	1.451	1.814	3.264	1.105	2.159	0.02874	7.60	7.88
0.6	1.451	2.418	3.869	1.310	2.559	0.03883	7.11	7.31
0.4	1.451	3.627	5.078	1.720	3.358	0.05748	6.61	6.58
0.2	1.451	7.254	8.705	2.948	5.757	0.11497	6.06	5.51

Table B-5 Optimization Results for Hydraulic Horsepower Method (10 gpm
Nozzle Sizes 10,10,10, m=1.953)

P_b/P_c	P_b	P_c	P_p	$P_c(opt)$	$P_b(opt)$	K'	$Q(opt)$	$d(opt)$
5.0	144.46	28.89	173.35	58.704	114.648	0.00726	148.27	12.90
4.8	144.46	30.10	174.56	59.111	115.444	0.00756	145.50	12.76
4.6	144.46	31.40	175.86	59.554	116.310	0.00789	142.69	12.61
4.4	144.46	32.83	177.29	60.038	117.254	0.00825	139.84	12.46
4.2	144.46	34.40	178.86	60.567	118.288	0.00864	136.94	12.30
4.0	144.46	36.12	180.58	61.150	119.425	0.00907	133.99	12.14
3.8	144.46	38.02	182.48	61.793	120.682	0.00955	130.98	11.97
3.6	144.46	40.13	184.59	62.509	122.079	0.01008	127.92	11.80
3.4	144.46	42.49	186.95	63.308	123.640	0.01067	124.80	11.61
3.2	144.46	45.14	189.60	64.207	125.397	0.01134	121.62	11.43
3.0	144.46	48.15	192.61	65.226	127.39	0.01210	118.36	11.23
2.8	144.46	51.59	196.05	66.391	129.662	0.01296	115.04	11.02
2.6	144.46	55.56	200.02	67.735	132.287	0.01396	111.63	10.80
2.4	144.46	60.19	204.65	69.303	135.349	0.01512	108.15	10.57
2.2	144.46	65.66	210.12	71.156	138.968	0.01649	104.56	10.33
2.0	144.46	72.23	216.69	73.380	143.310	0.01814	100.88	10.06
1.8	144.46	80.26	224.72	76.097	148.618	0.02016	97.09	9.78
1.6	144.46	90.29	234.75	79.495	155.253	0.02268	93.17	9.48
1.4	144.46	103.19	247.65	83.862	163.783	0.02592	89.12	9.15
1.2	144.46	120.38	264.84	89.686	175.157	0.03024	84.91	8.78
1.0	144.46	144.46	288.92	97.839	191.081	0.03629	80.53	8.37
0.8	144.46	180.58	325.04	110.069	214.966	0.04536	75.96	7.89
0.6	144.46	240.77	385.23	130.453	254.774	0.06048	71.14	7.32
0.4	144.46	361.15	505.61	171.219	334.391	0.09072	66.06	6.59
0.2	144.46	722.30	866.76	293.518	573.242	0.18143	60.64	5.52

Table B-6 Optimization Results for Hydraulic Horsepower Method (100 gpm
Nozzle Sizes 10,10,10 , $m=1.953$)

P_b/P_c	P_b	P_c	P_p	$P_c(opt)$	$P_b(opt)$	K'	$Q(opt)$	$d(opt)$
5.0	1.451	0.290	1.741	0.881	0.860	0.01396	10.00	11.38
4.8	1.451	0.302	1.753	0.887	0.866	0.01406	10.00	11.36
4.6	1.451	0.315	1.766	0.894	0.873	0.01416	10.00	11.34
4.4	1.451	0.330	1.781	0.901	0.880	0.01428	10.00	11.32
4.2	1.451	0.345	1.796	0.909	0.887	0.01440	10.00	11.30
4.0	1.451	0.363	1.814	0.918	0.896	0.01454	10.00	11.27
3.8	1.451	0.382	1.833	0.927	0.905	0.01469	10.00	11.24
3.6	1.451	0.403	1.854	0.938	0.916	0.01487	10.00	11.21
3.4	1.451	0.427	1.878	0.95	0.928	0.01506	10.00	11.17
3.2	1.451	0.453	1.904	0.963	0.941	0.01527	10.00	11.13
3.0	1.451	0.484	1.934	0.979	0.956	0.01551	10.00	11.09
2.8	1.451	0.518	1.969	0.996	0.973	0.01579	10.00	11.04
2.6	1.451	0.558	2.009	1.016	0.992	0.01611	10.00	10.98
2.4	1.451	0.605	2.055	1.04	1.015	0.01648	10.00	10.92
2.2	1.451	0.659	2.110	1.068	1.043	0.01692	10.00	10.85
2.0	1.451	0.725	2.176	1.101	1.075	0.01745	10.00	10.77
1.8	1.451	0.806	2.257	1.142	1.115	0.01810	10.00	10.67
1.6	1.451	0.907	2.358	1.193	1.165	0.01890	10.00	10.55
1.4	1.451	1.036	2.487	1.258	1.229	0.01994	10.00	10.41
1.2	1.451	1.209	2.660	1.346	1.314	0.02133	10.00	10.24
1.0	1.451	1.451	2.902	1.468	1.134	0.02327	10.00	10.02
0.9	1.451	1.612	3.063	1.55	1.513	0.02456	10.00	9.88
0.8	1.451	1.814	3.264	1.652	1.613	0.02618	10.00	9.73
0.6	1.451	2.418	3.869	1.957	1.911	0.03102	10.00	9.32
0.4	1.451	3.627	5.078	2.569	2.509	0.04072	10.00	8.71
0.2	1.451	7.254	8.705	4.404	4.301	0.06980	10.00	7.61

Table B-7 Optimization Results for Jet Impact Force Method (10 gpm
Nozzle Sizes 10,10,10, m=1.953)

P_b/P_c	P_b	P_c	P_p	$P_c(opt)$	$P_b(opt)$	K'	$Q(opt)$	$d(opt)$
5.0	144.46	28.89	173.35	87.707	85.645	0.02203	100.00	11.40
4.8	144.46	30.10	174.56	88.316	86.240	0.02218	100.00	11.38
4.6	144.46	31.40	175.86	88.978	86.887	0.02235	100.00	11.36
4.4	144.46	32.83	177.29	89.700	87.592	0.02253	100.00	11.33
4.2	144.46	34.40	178.86	90.491	88.364	0.02273	100.00	11.31
4.0	144.46	36.12	180.58	91.361	89.214	0.02295	100.00	11.28
3.8	144.46	38.02	182.48	92.323	90.153	0.02319	100.00	11.25
3.6	144.46	40.13	184.59	93.391	91.197	0.02346	100.00	11.22
3.4	144.46	42.49	186.95	94.585	92.363	0.02376	100.00	11.18
3.2	144.46	45.14	189.60	95.929	93.675	0.02410	100.00	11.14
3.0	144.46	48.15	192.61	97.452	95.162	0.02448	100.00	11.10
2.8	144.46	51.59	196.05	99.192	96.861	0.02492	100.00	11.05
2.6	144.46	55.56	200.02	101.200	98.822	0.02542	100.00	11.00
2.4	144.46	60.19	204.65	103.542	101.109	0.02601	100.00	10.93
2.2	144.46	65.66	210.12	106.311	103.813	0.02670	100.00	10.86
2.0	144.46	72.23	216.69	109.633	107.057	0.02754	100.00	10.78
1.8	144.46	80.26	224.72	113.694	111.022	0.02856	100.00	10.68
1.6	144.46	90.29	234.75	118.769	115.978	0.02983	100.00	10.56
1.4	144.46	103.19	247.65	125.295	122.351	0.03147	100.00	10.42
1.2	144.46	120.38	264.84	133.996	130.847	0.03366	100.00	10.25
1.0	144.46	144.46	288.92	146.178	142.742	0.03672	100.00	10.03
0.9	144.46	160.51	304.97	154.299	150.673	0.03876	100.00	9.90
0.8	144.46	180.58	325.04	164.450	160.585	0.04131	100.00	9.74
0.6	144.46	240.77	385.23	194.903	190.323	0.04896	100.00	9.33
0.4	144.46	361.15	505.61	255.811	249.799	0.06426	100.00	8.72
0.2	144.46	722.30	866.76	438.533	428.227	0.11015	100.00	7.62

Table B-8 Optimization Results for Jet Impact Force Method (100 gpm
Nozzle Sizes 10,10,10, m=1.953)

SP	BIT OPT.	BIT OPT.	CIRC.	CIRC	OPTIMU M	OPTIMU M	HHP	JIF	HHP	JIF
PESS.	HHP(Psi)	JIF(Psi)	HHP(Psi)	JIF(Psi)	JIF(GPM)	HHP(GP M)	HP	HP	\$	\$
1000	614	443	386	557	596	505	181	154	\$66.15	\$55.61
1050	644.7	465.15	405.3	584.85	569	477	179	155	\$65.86	\$55.94
1100	675.4	487.3	424.6	612.7	548	455	179	156	\$66.02	\$56.55
1150	706.1	509.45	443.9	640.55	531	437	180	158	\$66.49	\$57.36
1200	736.8	531.6	463.2	668.4	516	422	181	160	\$67.21	\$58.32
1250	767.5	553.75	482.5	696.25	504	409	183	163	\$68.10	\$59.40
1300	798.2	575.9	501.8	724.1	493	398	186	166	\$69.14	\$60.58
1350	828.9	598.05	521.1	751.95	484	389	188	169	\$70.29	\$61.82
1400	859.6	620.2	540.4	779.8	476	381	191	172	\$71.54	\$63.13
1450	890.3	642.35	559.7	807.65	469	373	194	176	\$72.86	\$64.49
1500	921	664.5	579	835.5	462	367	197	179	\$74.24	\$65.89
1550	951.7	686.65	598.3	863.35	456	361	201	183	\$75.68	\$67.33
1600	982.4	708.8	617.6	891.2	451	356	204	187	\$77.16	\$68.79
1650	1013.1	730.95	636.9	919.05	446	351	208	190	\$78.69	\$70.29
1700	1043.8	753.1	656.2	946.9	442	347	211	194	\$80.25	\$71.80
1750	1074.5	775.25	675.5	974.75	438	343	215	198	\$81.84	\$73.34
1800	1105.2	797.4	694.8	1002.6	434	339	219	202	\$83.47	\$74.90
1850	1135.9	819.55	714.1	1030.45	431	336	223	206	\$85.11	\$76.47
1900	1166.6	841.7	733.4	1058.3	428	333	227	210	\$86.78	\$78.06
1950	1197.3	863.85	752.7	1086.15	425	330	231	214	\$88.47	\$79.67
2000	1228	886	772	1114	422	327	235	218	\$90.18	\$81.28
2050	1258.7	908.15	791.3	1141.85	419	325	239	222	\$91.90	\$82.91
2100	1289.4	930.3	810.6	1169.7	417	323	243	226	\$93.64	\$84.54
2150	1320.1	952.45	829.9	1197.55	415	320	247	231	\$95.40	\$86.19
2200	1350.8	974.6	849.2	1225.4	413	318	251	235	\$97.17	\$87.84
2250	1381.5	996.75	868.5	1253.25	411	316	255	239	\$98.95	\$89.51
2300	1412.2	1018.9	887.8	1281.1	409	315	259	243	\$100.74	\$91.18
2350	1442.9	1041.05	907.1	1308.95	407	313	263	247	\$102.54	\$92.86
2400	1473.6	1063.2	926.4	1336.8	406	311	268	252	\$104.36	\$94.54
2450	1504.3	1085.35	945.7	1364.65	404	310	272	256	\$106.18	\$96.23
2500	1535	1107.5	965	1392.5	402	308	276	260	\$108.02	\$97.93
2550	1565.7	1129.65	984.3	1420.35	401	307	280	264	\$109.86	\$99.63
2600	1596.4	1151.8	1003.6	1448.2	400	306	285	269	\$111.71	\$101.34
2650	1627.1	1173.95	1022.9	1476.05	398	304	289	273	\$113.57	\$103.06

Table D-1 Cost Comparison at Different Standpipe Pressures: m=1.5

P	BIT OPT.	BIT OPT.	CIRC.	CIRC	OPTIMUM	OPTIM UM	HHP	JIF	HHP	JIF
PESS.	HHP(PSI)	JIF(PSI)	HHP(PSI)	JIF(PSI)	JIF(GPM)	HHP(G PM)	HP	HP	\$	\$
1000	600	429	400	571	603	520	182	151	\$66.43	\$54.44
1050	630	450	420	600	577	490	180	151	\$65.92	\$54.76
1100	660	471	440	629	555	466	179	153	\$65.89	\$55.35
1150	690	493	460	657	538	446	180	155	\$66.21	\$56.14
1200	720	514	480	686	523	430	181	157	\$66.78	\$57.08
1250	750	536	500	714	511	416	182	160	\$67.55	\$58.14
1300	780	557	520	743	500	404	184	162	\$68.47	\$59.28
1350	810	579	540	771	490	394	186	165	\$69.51	\$60.50
1400	840	600	560	800	482	385	189	169	\$70.65	\$61.78
1450	870	621	580	829	475	378	192	172	\$71.87	\$63.10
1500	900	643	600	857	468	371	195	176	\$73.16	\$64.47
1550	930	664	620	886	462	364	198	179	\$74.51	\$65.87
1600	960	686	640	914	457	359	201	183	\$75.91	\$67.31
1650	990	707	660	943	452	354	204	186	\$77.35	\$68.77
1700	1020	729	680	971	448	349	208	190	\$78.83	\$70.25
1750	1050	750	700	1000	444	345	211	194	\$80.34	\$71.75
1800	1080	771	720	1029	440	341	215	198	\$81.88	\$73.27
1850	1110	793	740	1057	436	338	219	202	\$83.44	\$74.81
1900	1140	814	760	1086	433	334	222	206	\$85.03	\$76.36
1950	1170	836	780	1114	430	331	226	210	\$86.65	\$77.93
2000	1200	857	800	1143	427	328	230	214	\$88.28	\$79.50
2050	1230	879	820	1171	425	326	234	218	\$89.93	\$81.09
2100	1260	900	840	1200	422	323	238	222	\$91.59	\$82.69
2150	1290	921	860	1229	420	321	242	226	\$93.27	\$84.30
2200	1320	943	880	1257	418	319	246	230	\$94.97	\$85.91
2250	1350	964	900	1286	416	317	250	234	\$96.67	\$87.54
2300	1380	986	920	1314	414	315	254	238	\$98.39	\$89.17
2350	1410	1007	940	1343	412	313	258	242	\$100.12	\$90.81
2400	1440	1029	960	1371	411	311	262	246	\$101.87	\$92.45
2450	1470	1050	980	1400	409	310	266	251	\$103.62	\$94.10
2500	1500	1071	1000	1429	408	308	270	255	\$105.38	\$95.76
2550	1530	1093	1020	1457	406	307	274	259	\$107.15	\$97.42
2600	1560	1114	1040	1486	405	305	278	263	\$108.93	\$99.09

Table D-2 Cost Comparison at Different Standpipe Pressures: m=1.6

SP	BIT OPT. HHP(PSI)	BIT OPT. JIF(PSI)	CIRC. HHP(PSI)	CIRC JIF(PSI)	OPTIMU M JIF(GPM)	OPTIMUM HHP(GPM)	HHP HP	JIF HP	HHP \$	JIF \$
PESS.)									
1000	630	459	370	541	587	490	180	157	\$65.94	\$56.88
1050	661	482	389	568	561	465	179	158	\$65.90	\$57.22
1100	693	505	407	595	540	445	180	159	\$66.26	\$57.84
1150	724	528	426	622	523	428	181	161	\$66.91	\$58.68
1200	756	551	444	649	509	414	183	164	\$67.78	\$59.67
1250	787	574	463	676	497	403	185	166	\$68.82	\$60.78
1300	819	597	481	703	486	393	187	169	\$69.98	\$61.98
1350	850	620	500	730	477	384	190	173	\$71.26	\$63.26
1400	881	643	519	757	469	376	194	176	\$72.62	\$64.60
1450	913	666	537	784	462	370	197	179	\$74.05	\$66.00
1500	944	689	556	811	455	364	200	183	\$75.54	\$67.43
1550	976	712	574	838	450	358	204	187	\$77.08	\$68.91
1600	1007	735	593	865	444	353	208	191	\$78.66	\$70.41
1650	1039	758	611	892	440	349	211	194	\$80.29	\$71.94
1700	1070	781	630	919	435	345	215	198	\$81.95	\$73.50
1750	1102	804	648	946	431	341	219	202	\$83.63	\$75.08
1800	1133	827	667	973	428	338	223	206	\$85.35	\$76.67
1850	1165	850	685	1000	424	335	227	210	\$87.08	\$78.29
1900	1196	873	704	1027	421	332	232	215	\$88.84	\$79.92
1950	1228	896	722	1054	418	329	236	219	\$90.62	\$81.56
2000	1259	919	741	1081	416	327	240	223	\$92.42	\$83.22
2050	1291	942	759	1108	413	324	244	227	\$94.23	\$84.89
2100	1322	965	778	1135	411	322	249	231	\$96.05	\$86.57
2150	1354	988	796	1162	409	320	253	236	\$97.90	\$88.25
2200	1385	1011	815	1189	407	318	257	240	\$99.75	\$89.95
2250	1417	1034	833	1216	405	317	262	244	\$101.62	\$91.66
2300	1448	1057	852	1243	403	315	266	248	\$103.49	\$93.37
2350	1480	1080	870	1270	401	313	270	253	\$105.38	\$95.10
2400	1511	1103	889	1297	399	312	275	257	\$107.28	\$96.82
2450	1543	1126	907	1324	398	310	279	261	\$109.19	\$98.56
2500	1574	1149	926	1351	396	309	284	266	\$111.11	\$100.30
2550	1606	1172	944	1378	395	308	288	270	\$113.03	\$102.05
2600	1637	1195	963	1405	394	306	293	274	\$114.97	\$103.80

Table D-3 Cost Comparison at Different Standpipe Pressures: m=1.7

SP	BIT OPT.	BIT OPT.	CIRC.	CIRC	OPTIMU M	OPTIMUM	HHP	JIF	HHP	JIF
PESS.	HHP(PSI)	JIF(PSI)	HHP(PSI)	JIF(PSI)	JIF(GPM))	HHP(GPM)	HP	HP	\$	\$
1000	643	474	357	526	579	479	180	160	\$65.87	\$57.91
1050	675	497	375	553	554	455	179	161	\$66.01	\$58.26
1100	707	521	393	579	533	437	180	162	\$66.54	\$58.91
1150	739	545	411	605	516	421	182	164	\$67.33	\$59.76
1200	771	568	429	632	502	408	184	166	\$68.33	\$60.77
1250	804	592	446	658	490	398	186	169	\$69.48	\$61.91
1300	836	616	464	684	480	388	189	172	\$70.76	\$63.14
1350	868	639	482	711	471	380	192	176	\$72.14	\$64.44
1400	900	663	500	737	463	373	196	179	\$73.59	\$65.81
1450	932	687	518	763	456	367	199	183	\$75.11	\$67.23
1500	964	711	536	789	449	361	203	186	\$76.69	\$68.70
1550	996	734	554	816	444	356	207	190	\$78.32	\$70.20
1600	1029	758	571	842	438	351	211	194	\$79.99	\$71.74
1650	1061	782	589	868	434	347	215	198	\$81.70	\$73.30
1700	1093	805	607	895	430	344	219	202	\$83.44	\$74.89
1750	1125	829	625	921	426	340	223	206	\$85.20	\$76.50
1800	1157	853	643	947	422	337	227	210	\$86.99	\$78.14
1850	1189	876	661	974	419	334	232	214	\$88.81	\$79.78
1900	1221	900	679	1000	416	331	236	218	\$90.64	\$81.45
1950	1254	924	696	1026	413	329	240	223	\$92.50	\$83.12
2000	1286	947	714	1053	410	326	245	227	\$94.37	\$84.82
2050	1318	971	732	1079	408	324	249	231	\$96.26	\$86.52
2100	1350	995	750	1105	405	322	254	235	\$98.16	\$88.23
2150	1382	1018	768	1132	403	320	258	240	\$100.07	\$89.96
2200	1414	1042	786	1158	401	318	263	244	\$102.00	\$91.69
2250	1446	1066	804	1184	399	317	267	248	\$103.94	\$93.43
2300	1479	1089	821	1211	398	315	272	253	\$105.89	\$95.18
2350	1511	1113	839	1237	396	314	276	257	\$107.85	\$96.94
2400	1543	1137	857	1263	394	312	281	261	\$109.82	\$98.71
2450	1575	1161	875	1289	393	311	286	266	\$111.80	\$100.48
2500	1607	1184	893	1316	391	310	290	270	\$113.79	\$102.26
2550	1639	1208	911	1342	390	308	295	275	\$115.79	\$104.04

Table D-4 Cost Comparison at Different Standpipe Pressures: m=1.8

SP PESS.	BIT OPT. HHP(PSI)	BIT OPT. JIF(PSI)	CIRC. HHP(PSI)	CIRC JIF(PSI)	OPTIMUM JIF(GPM)	OPTIMUM HHP(GPM)	HHP HP	JIF HP	HHP \$	JIF \$
1000	655	487	345	513	572	469	179	162	\$65.87	\$58.85
1050	688	512	362	538	546	447	180	163	\$66.19	\$59.21
1100	721	536	379	564	526	430	181	164	\$66.86	\$59.87
1150	753	560	397	590	509	416	183	167	\$67.78	\$60.74
1200	786	585	414	615	495	404	185	169	\$68.90	\$61.77
1250	819	609	431	641	484	393	188	172	\$70.16	\$62.92
1300	852	633	448	667	473	385	191	175	\$71.54	\$64.18
1350	884	658	466	692	464	377	195	178	\$73.00	\$65.51
1400	917	682	483	718	457	370	198	182	\$74.55	\$66.90
1450	950	706	500	744	450	364	202	185	\$76.16	\$68.35
1500	983	731	517	769	443	359	206	189	\$77.82	\$69.85
1550	1016	755	534	795	438	354	210	193	\$79.53	\$71.38
1600	1048	779	552	821	433	350	214	197	\$81.28	\$72.94
1650	1081	804	569	846	428	346	218	201	\$83.06	\$74.54
1700	1114	828	586	872	424	343	223	205	\$84.88	\$76.15
1750	1147	853	603	897	420	339	227	209	\$86.72	\$77.80
1800	1179	877	621	923	417	336	231	213	\$88.59	\$79.46
1850	1212	901	638	949	413	333	236	217	\$90.47	\$81.13
1900	1245	926	655	974	410	331	240	222	\$92.38	\$82.83
1950	1278	950	672	1000	408	329	245	226	\$94.31	\$84.54
2000	1310	974	690	1026	405	326	249	230	\$96.25	\$86.26
2050	1343	999	707	1051	403	324	254	235	\$98.21	\$88.00
2100	1376	1023	724	1077	400	322	259	239	\$100.18	\$89.74
2150	1409	1047	741	1103	398	321	263	243	\$102.16	\$91.50
2200	1441	1072	759	1128	396	319	268	248	\$104.16	\$93.26
2250	1474	1096	776	1154	394	317	273	252	\$106.17	\$95.04
2300	1507	1121	793	1179	392	316	278	257	\$108.19	\$96.82
2350	1540	1145	810	1205	391	314	282	261	\$110.22	\$98.61
2400	1572	1169	828	1231	389	313	287	265	\$112.26	\$100.41
2450	1605	1194	845	1256	388	312	292	270	\$114.30	\$102.22
2500	1638	1218	862	1282	386	310	297	274	\$116.36	\$104.03
2550	1671	1242	879	1308	385	309	301	279	\$118.43	\$105.85
2600	1703	1267	897	1333	384	308	306	283	\$120.50	\$107.68
2650	1736	1291	914	1359	382	307	311	288	\$122.58	\$109.51
2700	1769	1315	931	1385	381	306	316	292	\$124.67	\$111.34

Table D-5 Cost Comparison at Different Standpipe Pressures: m=1.9

SP	BIT OPT.	BIT OPT.	CIRC.	CIRC	OPTIMUM	OPTIMUM	HHP	JIF	HHP	JIF
PESS.	HHP(PSI)	JIF(PSI)	HHP(PSI)	JIF(PSI)	JIF(GPM)	HHP(GPM)	HP	HP	\$	\$
1000	667	500	333	500	564	461	179	165	\$65.93	\$59.69
1050	700	525	350	525	539	440	180	165	\$66.41	\$60.06
1100	733	550	367	550	519	424	181	167	\$67.21	\$60.73
1150	767	575	383	575	503	411	184	169	\$68.25	\$61.62
1200	800	600	400	600	489	399	186	171	\$69.48	\$62.67
1250	833	625	417	625	478	390	190	174	\$70.84	\$63.84
1300	867	650	433	650	467	382	193	177	\$72.31	\$65.12
1350	900	675	450	675	459	374	197	181	\$73.86	\$66.47
1400	933	700	467	700	451	368	200	184	\$75.49	\$67.89
1450	967	725	483	725	444	363	204	188	\$77.18	\$69.36
1500	1000	750	500	750	438	358	209	192	\$78.92	\$70.88
1550	1033	775	517	775	432	353	213	195	\$80.71	\$72.44
1600	1067	800	533	800	427	349	217	199	\$82.53	\$74.03
1650	1100	825	550	825	423	345	222	204	\$84.39	\$75.65
1700	1133	850	567	850	419	342	226	208	\$86.27	\$77.29
1750	1167	875	583	875	415	339	231	212	\$88.19	\$78.96
1800	1200	900	600	900	411	336	235	216	\$90.12	\$80.65
1850	1233	925	617	925	408	333	240	220	\$92.08	\$82.36
1900	1267	950	633	950	405	331	244	225	\$94.05	\$84.08
1950	1300	975	650	975	402	329	249	229	\$96.05	\$85.82
2000	1333	1000	667	1000	400	326	254	233	\$98.06	\$87.57
2050	1367	1025	683	1025	397	325	259	238	\$100.08	\$89.33
2100	1400	1050	700	1050	395	323	264	242	\$102.12	\$91.11
2150	1433	1075	717	1075	393	321	268	247	\$104.17	\$92.90
2200	1467	1100	733	1100	391	319	273	251	\$106.23	\$94.69
2250	1500	1125	750	1125	389	318	278	255	\$108.31	\$96.50
2300	1533	1150	767	1150	387	316	283	260	\$110.39	\$98.31
2350	1567	1175	783	1175	386	315	288	264	\$112.49	\$100.13
2400	1600	1200	800	1200	384	314	293	269	\$114.59	\$101.96
2450	1633	1225	817	1225	383	312	298	274	\$116.71	\$103.80
2500	1667	1250	833	1250	381	311	303	278	\$118.83	\$105.64
2550	1700	1275	850	1275	380	310	308	283	\$120.96	\$107.49
2600	1733	1300	867	1300	379	309	313	287	\$123.10	\$109.35
2650	1767	1325	883	1325	377	308	318	292	\$125.24	\$111.21

Table D-6 Cost Comparison at Different Standpipe Pressures: m=2.0

SP	BIT OPT.	BIT OPT.	CIRC.	CIRC	OPTIMUM	OPTIMUM	HHP	JIF	HHP	JIF
PESS.	HHP(PSI)	JIF(PSI)	HHP(PSI)	JIF(PSI)	JIF(GPM)	HHP(GPM)	HP	HP	\$	\$
1000	677	512	323	488	557	454	179	167	\$66.04	\$60.45
1050	711	538	339	512	533	435	180	167	\$66.66	\$60.83
1100	745	563	355	537	513	419	182	169	\$67.59	\$61.51
1150	779	589	371	561	497	407	185	171	\$68.74	\$62.41
1200	813	615	387	585	483	396	188	173	\$70.06	\$63.48
1250	847	640	403	610	472	387	191	176	\$71.51	\$64.67
1300	881	666	419	634	462	379	195	179	\$73.07	\$65.97
1350	915	691	435	659	453	372	199	183	\$74.71	\$67.34
1400	948	717	452	683	445	366	203	186	\$76.41	\$68.78
1450	982	743	468	707	439	361	207	190	\$78.18	\$70.27
1500	1016	768	484	732	432	356	211	194	\$79.99	\$71.82
1550	1050	794	500	756	427	352	216	198	\$81.85	\$73.40
1600	1084	820	516	780	422	348	220	202	\$83.75	\$75.01
1650	1118	845	532	805	418	345	225	206	\$85.67	\$76.66
1700	1152	871	548	829	414	341	229	210	\$87.62	\$78.33
1750	1185	896	565	854	410	338	234	214	\$89.60	\$80.02
1800	1219	922	581	878	406	336	239	219	\$91.61	\$81.73
1850	1253	948	597	902	403	333	244	223	\$93.63	\$83.47
1900	1287	973	613	927	400	331	249	227	\$95.67	\$85.21
1950	1321	999	629	951	397	329	253	232	\$97.73	\$86.98
2000	1355	1024	645	976	395	327	258	236	\$99.80	\$88.76
2050	1389	1050	661	1000	393	325	263	240	\$101.89	\$90.55
2100	1423	1076	677	1024	390	323	268	245	\$103.99	\$92.35
2150	1456	1101	694	1049	388	322	273	249	\$106.10	\$94.16
2200	1490	1127	710	1073	386	320	278	254	\$108.23	\$95.99
2250	1524	1152	726	1098	384	319	283	258	\$110.37	\$97.82
2300	1558	1178	742	1122	383	317	288	263	\$112.51	\$99.66
2350	1592	1204	758	1146	381	316	293	268	\$114.67	\$101.51
2400	1626	1229	774	1171	380	315	298	272	\$116.84	\$103.37
2450	1660	1255	790	1195	378	313	304	277	\$119.01	\$105.23
2500	1694	1280	806	1220	377	312	309	281	\$121.20	\$107.10
2550	1727	1306	823	1244	375	311	314	286	\$123.39	\$108.98
2600	1761	1332	839	1268	374	310	319	291	\$125.59	\$110.86
2650	1795	1357	855	1293	373	309	324	295	\$127.80	\$112.75

Table D-7 Cost Comparison at Different Standpipe Pressures: m=2.1

SP	BIT OPT.	BIT OPT.	CIRC.	CIRC	OPTIMUM	OPTIMUM	HHP	JIF	HHP	JIF
PESS.	HHP(PSI)	JIF(PSI)	HHP(PSI)	JIF(PSI)	JIF(GPM)	HHP(GPM)	HP	HP	\$	\$
1000	688	524	313	476	551	448	180	168	\$66.19	\$61.13
1050	722	550	328	500	526	430	181	169	\$66.94	\$61.52
1100	756	576	344	524	507	415	183	170	\$67.98	\$62.21
1150	791	602	359	548	491	403	186	173	\$69.23	\$63.13
1200	825	629	375	571	477	393	189	175	\$70.64	\$64.21
1250	859	655	391	595	466	385	193	178	\$72.18	\$65.42
1300	894	681	406	619	456	377	197	181	\$73.82	\$66.73
1350	928	707	422	643	448	371	201	185	\$75.53	\$68.12
1400	963	733	438	667	440	365	205	188	\$77.31	\$69.58
1450	997	760	453	690	433	360	209	192	\$79.15	\$71.10
1500	1031	786	469	714	427	355	214	196	\$81.04	\$72.66
1550	1066	812	484	738	422	351	218	200	\$82.96	\$74.26
1600	1100	838	500	762	417	348	223	204	\$84.92	\$75.90
1650	1134	864	516	786	413	344	228	208	\$86.91	\$77.57
1700	1169	890	531	810	409	341	233	212	\$88.93	\$79.26
1750	1203	917	547	833	405	338	238	217	\$90.97	\$80.98
1800	1238	943	563	857	401	336	242	221	\$93.04	\$82.71
1850	1272	969	578	881	398	333	247	225	\$95.12	\$84.47
1900	1306	995	594	905	395	331	252	230	\$97.22	\$86.24
1950	1341	1021	609	929	393	329	257	234	\$99.34	\$88.03
2000	1375	1048	625	952	390	327	262	239	\$101.48	\$89.83
2050	1409	1074	641	976	388	325	268	243	\$103.63	\$91.65
2100	1444	1100	656	1000	386	324	273	248	\$105.79	\$93.47
2150	1478	1126	672	1024	384	322	278	252	\$107.96	\$95.31
2200	1513	1152	688	1048	382	321	283	257	\$110.15	\$97.16
2250	1547	1179	703	1071	380	319	288	261	\$112.35	\$99.02
2300	1581	1205	719	1095	378	318	293	266	\$114.55	\$100.88
2350	1616	1231	734	1119	377	317	299	270	\$116.77	\$102.76
2400	1650	1257	750	1143	375	316	304	275	\$119.00	\$104.64
2450	1684	1283	766	1167	374	314	309	280	\$121.23	\$106.53
2500	1719	1310	781	1190	372	313	314	284	\$123.47	\$108.43
2550	1753	1336	797	1214	371	312	320	289	\$125.72	\$110.33
2600	1788	1362	813	1238	370	311	325	294	\$127.98	\$112.24
2650	1822	1388	828	1262	368	311	330	298	\$130.25	\$114.16

Table D-8 Cost Comparison at Different Standpipe Pressures: m=2.2

SP	BIT OPT.	BIT OPT.	CIRC.	CIRC	OPTIMUM	OPTIMUM	HHP	JIF	HHP	JIF
PESS.	HHP(PSI)	JIF(PSI)	HHP(PSI)	JIF(PSI)	JIF(GPM)	HHP(GPM)	HP	HP	\$	\$
1000	688	524	313	476	551	448	180	168	\$66.19	\$61.13
1050	722	550	328	500	526	430	181	169	\$66.94	\$61.52
1100	756	576	344	524	507	415	183	170	\$67.98	\$62.21
1150	791	602	359	548	491	403	186	173	\$69.23	\$63.13
1200	825	629	375	571	477	393	189	175	\$70.64	\$64.21
1250	859	655	391	595	466	385	193	178	\$72.18	\$65.42
1300	894	681	406	619	456	377	197	181	\$73.82	\$66.73
1350	928	707	422	643	448	371	201	185	\$75.53	\$68.12
1400	963	733	438	667	440	365	205	188	\$77.31	\$69.58
1450	997	760	453	690	433	360	209	192	\$79.15	\$71.10
1500	1031	786	469	714	427	355	214	196	\$81.04	\$72.66
1550	1066	812	484	738	422	351	218	200	\$82.96	\$74.26
1600	1100	838	500	762	417	348	223	204	\$84.92	\$75.90
1650	1134	864	516	786	413	344	228	208	\$86.91	\$77.57
1700	1169	890	531	810	409	341	233	212	\$88.93	\$79.26
1750	1203	917	547	833	405	338	238	217	\$90.97	\$80.98
1800	1238	943	563	857	401	336	242	221	\$93.04	\$82.71
1850	1272	969	578	881	398	333	247	225	\$95.12	\$84.47
1900	1306	995	594	905	395	331	252	230	\$97.22	\$86.24
1950	1341	1021	609	929	393	329	257	234	\$99.34	\$88.03
2000	1375	1048	625	952	390	327	262	239	\$101.48	\$89.83
2050	1409	1074	641	976	388	325	268	243	\$103.63	\$91.65
2100	1444	1100	656	1000	386	324	273	248	\$105.79	\$93.47
2150	1478	1126	672	1024	384	322	278	252	\$107.96	\$95.31
2200	1513	1152	688	1048	382	321	283	257	\$110.15	\$97.16
2250	1547	1179	703	1071	380	319	288	261	\$112.35	\$99.02
2300	1581	1205	719	1095	378	318	293	266	\$114.55	\$100.88
2350	1616	1231	734	1119	377	317	299	270	\$116.77	\$102.76
2400	1650	1257	750	1143	375	316	304	275	\$119.00	\$104.64
2450	1684	1283	766	1167	374	314	309	280	\$121.23	\$106.53
2500	1719	1310	781	1190	372	313	314	284	\$123.47	\$108.43
2550	1753	1336	797	1214	371	312	320	289	\$125.72	\$110.33
2600	1788	1362	813	1238	370	311	325	294	\$127.98	\$112.24
2650	1822	1388	828	1262	368	311	330	298	\$130.25	\$114.16

Table D-9 Cost Comparison at Different Standpipe Pressures: m=2.3